A STUDY ON COMBINATION OF SERIES ACTIVE POWER FILTER AND SHUNT PASSIVE POWER FILTER FOR HARMONIC COMPENSATION

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by

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School of Electrical Engineering & Telecommunication
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CERTIFICATION OF APPROVAL

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(Associate Professor Fazlur Rahman)

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FEBRUARY 2006

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ABSTRACT

This project is carried out to study on the performance of combination of series active power filter and shunt passive power filter for harmonic compensation through simulation. Two different control methods which are instantaneous active and reactive power (p-q method) and instantaneous active and reactive current component (i_d-i_q method) are applied to the combined filter and the comparative study of their performance is carried out. The simulation is carried out using MATLAB Simulink – SimPower System block and a model of a complete network with a thyristor converter driven load was developed. The model was simulated in several phases; without any of the filter operating on it, with shunt passive filter acting alone, with a series active filter acting alone and with combination of both filters in order to examine the role of each filter involved. For each of the simulation, the THD of input line current is used as a performance measure. The studies had shown that the series active filter have a small effect in compensating the harmonic current while the shunt passive filter had a more significant role to compensate the harmonic current. The combination of both filters had enhanced significantly the ability of the filter to compensate the harmonic current. The simulation of the combined filter is extended by applying the two different control methods with three different conditions of supply voltage; a balanced and sinusoidal, unbalanced and sinusoidal and balanced and non-sinusoidal voltage. From the analysis of the harmonic content in the input line current (THD), it can be stated that under balanced and sinusoidal supply, p-q method and i_d-i_q method have the same performance in compensating the harmonic. Nevertheless, under unbalanced and non-sinusoidal supply, the i_d-i_q method had given a slightly better performance for harmonic compensation. Despite this slightly better performance of i_d-i_q method, it can be conclude that it does not have much significant impact for the combination of series active filter and shunt passive filter in compensating the harmonic.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF STUDY

The development of technology nowadays had enhanced the usage of the power electronic equipment in many applications. The growing and widespread use of electronic equipment in household appliances, and ac drives in daily routine application is becoming noticeable. These equipments use more and more diode rectifiers with smoothing dc capacitors, which present themselves as nonlinear loads. Harmonics generated by these loads have become a major issue. Diode rectifier with smoothing capacitors behaves as a harmonic voltage source instead of a harmonic current source [1]. The use of shunt passive filter was an acceptable method in compensating the harmonic current in early days but its inability to compensate for nonlinear load had discouraged its application and later replaced by shunt active filter alone that give an effective compensation of the nonlinear load. However, shunt active filter is found to be less practical to compensate for harmonic voltage source type applications because it requires a high VA-power rating, and thus it is not economical. Apart from that, the series active filter alone was found to be able to compensate for harmonic voltage source type but it cannot compensate for the harmonic current, which discourage its application.

Due to these issues, a combination of series active filter in parallel with passive filter was found to be an alternative way to provide a good compensation of harmonics with a lower cost [1, 2, 3]. It has been shown that current-source nonlinear loads and voltage- source nonlinear loads have dual relations to each other in circuits and properties, and that the parallel filters and series filters are suited for current-source and voltage-source loads, respectively [1]. The combined system was found to be able to compensate for the nonlinear load effectively with lower initial running cost [3] due to low VA rating of series active filter. It is able to compensate the current harmonic and voltage unbalance simultaneously [2] and is suitable for compensation of cycloconverter driven load [4]. However, the implementation of the combined series active filter and shunt passive filter is still in the laboratory stage and a further analysis of the system need to be conducted. Since the control method used in various studies so far only focused on using an instantaneous active and reactive power theory (p-q method) only, the possibility of enhancing the performance by using an instantaneous active and reactive current component (i_d-i_q method) for a combination of series active filter and shunt passive filter is investigated.

1.2 PROBLEM STATEMENT

In the wide ranges of active filter application, researchers had started to give attention to series active power filter (SAPF), even though shunt active filter or commonly known as active filter is more favorable as they are widely used in application field. Shunt active filter is found to have several drawbacks which are that the rated power required is high and is uneconomical to compensate for the diode rectifier with smoothing capacitor since it presented a harmonic voltage source type load. One of the alternatives to overcome this problem is a combination of series active power filter and shunt passive filter which can compensate for harmonic current and voltage unbalance simultaneously. At present, the combined systems being proposed by several researchers are only based on the instantaneous active and reactive power (p-q method) in generating the reference harmonics current. In this method, it requires the multiplication of the line voltage and line current in order to obtain the active and reactive power of the system. This active and reactive power is filtered out to get its harmonic component and is transformed back into the reference harmonics current required. The multiplication of the line voltage and current result in additional disturbances to the system and causes a less effective compensation. In the work done by [5], an instantaneous active and reactive current component i_d-i_q method was proposed to replace the p-q method in the shunt active filter. It shows that the proposed method had given a better result in compensating the current harmonic of the system in the case of nonlinear loads and unbalanced source conditions. In i_d-i_q method, the reference harmonics current is obtained from the active and reactive current components instead of the power components which eliminates the multiplication process and thus reduces the disturbances in the reference harmonic current. The additional disturbances when using the p-q method under non-ideal mains voltage can be noticeable and causes a less effective current compensation. Even though the supply from the main source is usually sinusoidal and balanced, at the point of coupling (PCC), the mains voltages may be unbalanced and non-sinusoidal. Furthermore, the supply harmonic current content may be constantly changing due to load current needs and random nature of network topology [5]. Thus, a study on the combination of series active power filters and shunt passive filter using both control method may be suitable and are analyzed when operated under different voltage condition to ascertain a suitable control strategy method.

1.3 OBJECTIVES AND SCOPE OF STUDY

The purpose of this research-based and simulation-based project was to study and to conduct a theoretical study on the combination of series active power filter and shunt passive filter to compensate the supply current harmonic. It aims to produce a comprehensive finding on the improvement of series APF performance on harmonic compensation.

Basically, the objectives of the project are:

1. To develop the combination of a series active filter with shunt passive filter using MATLAB SIMULINK.
2. To analyze the performance of the filter in compensating the harmonic current and voltage caused by the distorted supply and three-phase thyristor converter as well as diode rectifier.
3. To apply the instantaneous active and reactive current component (i_d-i_q) method instead of the instantaneous real and imaginary power method.

In order to achieve the objectives outlined above, the student is expected to perform the theoretical study on the filter topology proposed and other type of active filters available. The student will also develop a model using MATLAB Simulink in order to produce the result for different type of harmonic sources. The result obtained will be analyzed by the degree of harmonic content of the supply current waveform produced and by comparing with available results.

CHAPTER 2

LITERATURE REVIEW

2.1 HARMONIC SOURCES AND ANALYSIS

There are many power electronics equipment usage and other type of loads that contribute to the injection of the harmonics in power network. These nonlinear loads draw non-sinusoidal current from the utilities and cause the distortion in the line voltages and currents. The harmonic producing loads had been classified as identified and unidentified loads [6] or harmonic current source and harmonic voltage source [1].

2.1.1 Harmonic Current Sources

Phase-controlled thyristor rectifier, cycloconverter and arc furnace are typically characterized under this type [6, 8]. A common harmonic current source is the thyristor rectifier where the harmonic always result from the switching operation. In a typical thyristor rectifier, a constant dc current is produced with the large enough value of the dc inductance [1]. Its ac side current is not affected by the circuit parameters, thus the harmonic current content and characteristic are less dependent upon the ac side [1]. Considering this fact, this type of harmonic source is behaves like a current source and is said to be harmonic current source.

2.1.2 Harmonic Voltage Sources

A typical and common harmonic voltage source is the diode rectifier with smoothing dc capacitor [1, 6]. A multiple low-power diode rectifier which usually used as a utility interface in electrical appliances can inject a large amount of harmonic to the power distribution systems [6]. For system containing diode rectifier, the current waveform on load side is distorted and its harmonic amplitude is greatly affected by ac side while the rectifier load voltage is characteristic and less dependent on ac impedance [1]. Thus, the diode rectifier with dc filter capacitor can be considered as harmonic voltage source type since it behaves like a voltage source instead of a current source. A shunt active filter was found to be not effective to compensate for this type of harmonic sources [7].

2.2 SHUNT PASSIVE FILTER

Early development of harmonic current filter had encouraged the use of shunt passive filters to compensate the disturbance caused by the load as the harmonic interference problem became increasingly serious [1, 3]. However, shunt passive filter had several disadvantages that discourage their application. The main problem is that it does not have the capability to change its compensation characteristic following the dynamic changes of nonlinear load [9]. The performance of the shunt filter is also dependent on power system parameter and the probability of 'harmonic amplifying phenomena' is undesirable [3]. From the technical point of view, the determination of the inductance, L and capacitor, C value is very critical due to the fact that only a small design tolerance allowed [9]. Furthermore, shunt passive filter had also generated reactive power at fundamental frequency that changes the system voltage regulation [9]. Due to these drawbacks of shunt passive filter, methods to improve the compensation characteristic of the filter have been developed. Shunt active filter, series active filter and hybrid filter were identified as alternatives of shunt passive filter [6]. For hybrid filter, there are two configurations were proposed which are the shunt passive filter connected in parallel with series active filter and series active filter connected in series with shunt active filter [2, 3, 9].

2.3 ACTIVE POWER FILTER

2.3.1 Development of work on Active filter

In early days, shunt passive filter was widely used in industrial applications to suppress the harmonics in power system [3]. However, increasing use of bulk thyristor converter which produced nonlinear current harmonic had discouraged the usage of shunt passive filter [3]. Shunt active filter was extensively studied and the concept was introduced in 1971 by H.Sasaki and T.Machida [21]. Further development of shunt active filter consisting of PWM inverter using power transistor was presented by L.Gyugyi and E.C. Strycula in 1976 [22]. The concept of series filter was also proposed in their work but no significant attention was given to it. Many researches were conducted in shunt active filter using different control approaches and other improvements to ensure its practicality in industrial applications [23, 24]. There were only a few researchers focusing on series active filters [8, 11]. The proliferations in power electronics devices introduce the use of diode rectifier with smoothing capacitor. They produce 'harmonic voltage source' instead of 'harmonic current source' that led to the proposal of a new approach to combine series active filter and shunt passive filter in order to overcome the problem in 1988 [3]. The application of the combined system to compensate for fluctuating load such as cycloconverter was investigated and the compensation characteristic as well as the new control approach was proposed in [4].

Further investigation and work on the new approach has been carried out to compensate harmonic current as well as voltage unbalance [2]. The advantage of the new combined system is that it is able to effectively compensate for current harmonic with a low power rated filter compared to the load [2, 4]. In the years that followed, more work on series active filter was done with the proposed hybrid scheme combining series APF in series with shunt passive filter [2, 3, 9]. A series active power filter based on a sinusoidal current-controlled voltage-source inverter was proposed instead of sinusoidal voltage-controlled in 1997 [8]. Another new combination approach of series APF is the hybrid filter which aim to improve passive filter compensation. One of the papers had shown that the performance of the filter was improved for high voltage nonlinear load and proved that the schemes are able to compensate displacement power factor and current harmonics simultaneously [9].

2.3.2 Type of active power filter

Active power filter can be categorized based on the type of converter, topology, control scheme and compensation characteristics [10]. However, the most accepted classification is based on its topology, which is shunt, series or hybrid [10]. Since active power filter had become an extensive area of research due to the growth of power electronic applications, many work and studies were developed [2-6]. Different configuration or topology of active filter provides different performance of harmonic compensation [10]. A brief description of shunt, series and hybrid active filter is presented to see the different approach in each filter.

Shunt Active Power Filter

As the name implies, this type of active power filter is connected in parallel with the power distribution line. It is normally implemented with PWM voltage source inverter and widely studied and developed in order to enhance its performance [3]. Researches have been carried out on implementing this filter with PWM current source inverter; however it is still not yet put into practice. Shunt active filter operate as a controllable current source where it compensates current harmonics by injecting an equal but opposite compensating current to the line [1, 10]. The current injected by the filter will cancel out the harmonic current in the load [10]. Shunt active filter is effective in compensating the harmonic current produced by load considered as harmonic current source and is less practical to compensate for 'harmonic voltage sources', usually produce by diode rectifier and capacitor bank [1]. This is because for harmonic voltage source, the ac impedance to the load is lowered and causes large harmonic current to flow into the load. This in turn increased the required VA rating of shunt active filter and makes it uneconomical and impractical to compensate harmonic voltage source type [1]. These drawbacks of shunt active filter have encouraged a few researches to look into another alternative which use series active power filter. Figure 2.1 shows the basic configuration of the shunt active filter.

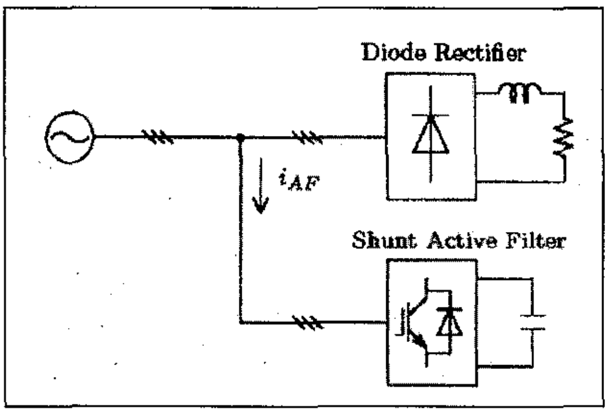


Figure 2.1: Basic configuration of shunt active filter

Series active filter

Series active power filters were introduced by the end of 1980s [10] and it is placed in series between ac source and the load. Principally, it is to present high impedance to harmonic current and thus blocking harmonic current flow from the load to the ac source and from ac source to the load side [1]. This filter can compensate effectively for harmonic of the source current from its compensation characteristic derived in [1]. It is effective means in solving the voltage sags problem where continuous real dynamic compensating can be implemented and at the same time it has a rapid response [10]. Series active filter was also shown to be able to reduce terminal harmonic voltage which ensures a good quality voltage waveform can be supplied to the load [11]. The drawback of the series active filter acting alone is that it is unable to cater for the harmonic current distortion but it is applicable to ensure a good sinusoidal voltage supply waveform. The compensation characteristic analysis of series active filter compensating harmonic current source had shown that the filter cannot compensate for this type of harmonic but can be realized by combining series active filter with shunt passive filter [1]. By doing so, the harmonic current and voltage source should be able to be compensated. Several researches had given an attention in the combined system of series active filter and shunt active filter [2, 3]. Figure 2.2 shows the basic configuration of the series active filter.

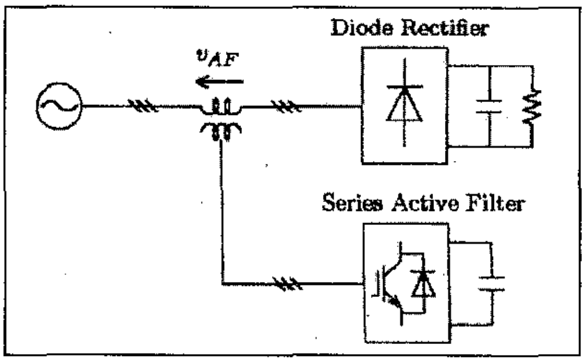


Figure 2.2: Basic configuration of the series active filter [12]

The difference between shunt active filter and series active filter can be categorized into several categories as shown in table 2.1 [6]. It shows that series active filter is acting as voltage source and is effective in compensating harmonic produces by diode rectifiers.

Table 2.1: Comparison of shunt and series active filters standing alone

	Shunt active filter	Series active filter
Power circuit	Voltage-fed PWM inverter with current minor loop	Voltage-fed PWM inverter without current minor loop
Active filter act as	Current source	Voltage source
Harmonic-producing load suitable	Diode or thyristor rectifiers with inductive loads & cycloconverters	Large capacity diode rectifiers with capacitive loads
Additional function	Reactive power compensation	AC voltage regulation
Present situation	Commercial stage	Laboratory level

Hybrid Active Power Filter

The possibility of combining shunt passive filter, shunt active filter and series active filter is continuously being researched with the intention to enhance the performance of the filter acting alone [2, 3, 5, 6, 8, 9]. This combination filter is named hybrid. There are three hybrid filters extensively being studied, which are a shunt active filter with shunt passive filter, a series active filter connected in parallel with shunt passive filter and series active filter connected in series with shunt passive filter [6]. Shunt active filter combined with shunt passive filter was already in the commercial stages since the availability of shunt active filter and also the shunt passive filter makes it easier to implement [6]. Harmonic compensation for this type of filter worked as it with shunt active filter and the shunt passive filter help in compensating the major harmonic order [6]. The second type of filter, the combination of series active filter and shunt passive filter is still in the field testing stage and it is still being researched [6]. The third type of hybrid filter which is a series active filter connected in series with shunt passive filter that is proposed to improve the compensation characteristics of passive filter [4, 6, 9].

The principle of operation of the third hybrid active filter is that the connection of active power filter in series through coupling transformer imposes a voltage signal at the primary terminal [4, 9]. This forces current harmonics to circulate through the passive filter, thus improving the compensation characteristic where it is independent of the filter parameter namely the variation in the resonant frequency [4]. The power factor of the power distribution system can be adjusted by controlling the fundamental voltage amplitude across the coupling transformer [4]. This hybrid active power filter is very suitable to compensate for nonlinear load with high power and medium voltage such as large power ac drives with cycloconverter or for compensation of arc furnace [4, 9]. The experiment had verified that hybrid active filter can compensate the displacement power factor and current harmonic simultaneously [4]. Table 2.2 shows the comparison between the three hybrid active and passive filters [6] with their respective figures in figure 2.3, 2.4 and 2.5. The detail of the second type of hybrid filter; combination of series active filter with shunt passive filter is discussed in detail in the next section.

Table 2.2: Comparison of hybrid active and passive filters [6]

	Shunt active with shunt passive filter	**Series active filter combined with shunt passive filter**	**Series active filter connected in series with shunt passive filter**
Power circuit of active filter	Voltage-fed PWM inverter with current minor loop	Voltage-fed PWM inverter without current minor loop	Voltage-fed PWM inverter with or without current minor loop
Function of active filter	Harmonic compensation	Harmonic isolation	Harmonic isolation or compensation
Advantages	• General shunt active filter applicable • Reactive power controllable	• The existing shunt passive filter applicable • Harmonic current do not flow through active filter	• Existing shunt passive filter applicable • Easy protection of active filter
Problem or issues	• Share compensation in frequency domain between active filter and passive filter	• Difficult to protect active filter against over current • No reactive power control	• No reactive power control
Present situation	Commercial stage	Field testing	Coming into market
System Configuration	Figure 2.3	Figure 2.4	Figure 2.5

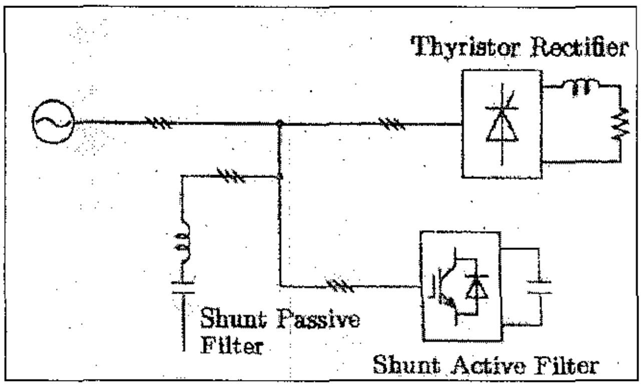


Figure 2.3: System configuration of shunt active filter with shunt passive filter

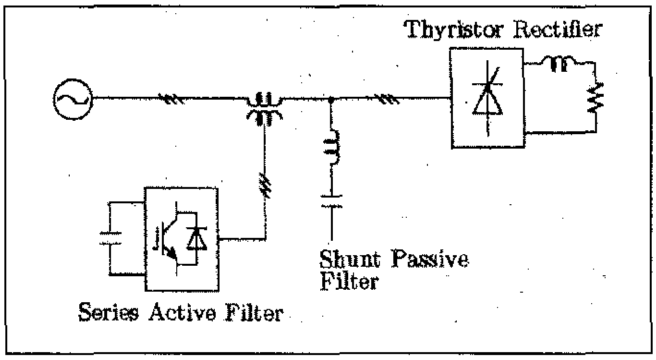


Figure 2.4: The system configuration of series active filter with shunt passive filter

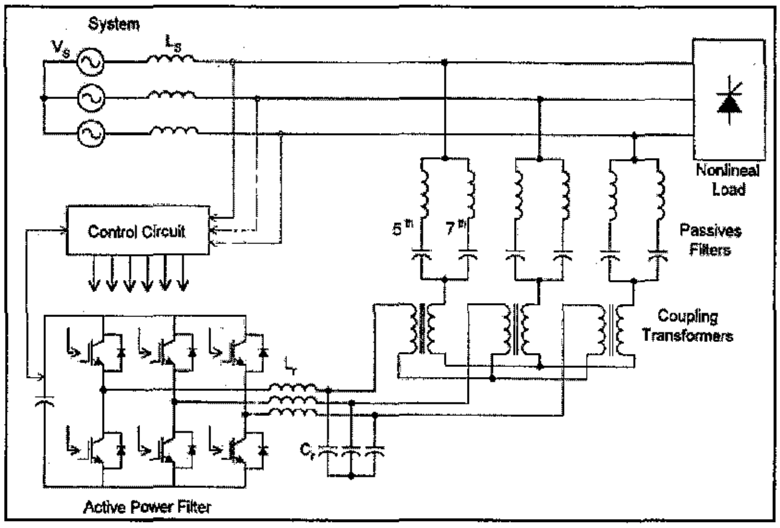


Figure 2.5: The system configuration of series active filter connected in series with shunt passive filter

2.4 COMBINATION OF SERIES ACTIVE POWER FILTER (SAPF) WITH SHUNT PASSIVE FILTER

The basic configuration of the filter is shown in figure 2.4. By combining SAPF with shunt passive filter, the performance of both filters standing alone to compensate for harmonic is significantly improved [1–3]. Analysis had shown that by combining both of the filters, both type of harmonic sources; harmonic voltage sources and harmonic current sources can be compensated [1]. The principle of operation for this type of filter is that the series active filter operates as a harmonic isolator by imposing high impedance to the line and forcing the load current harmonic to circulate through the passive filter [2, 3, 12]. The passive filter is designed in such that it can compensate the current harmonic usually the 5^{th} and 7^{th} order harmonic [2, 3]. The main advantage of using this configuration is that the rated power of the series active power filters only a fraction of the load kVA rating which is around 5% [10]. This type of configuration had been proposed in several papers that laid out the control method, system configuration and the compensation principle [2, 3, 13].

2.4.1 System configuration

Basic configuration of the system is as in figure 2.4. There are two possible configurations proposed as shown in figure 2.6 and 2.7 with only a slight different.

In figure 2.6, the series active filter used three single phase PWM voltage source inverter (PWM-VSI) [3] while the other configuration used the three phase PWM-VSI [2].

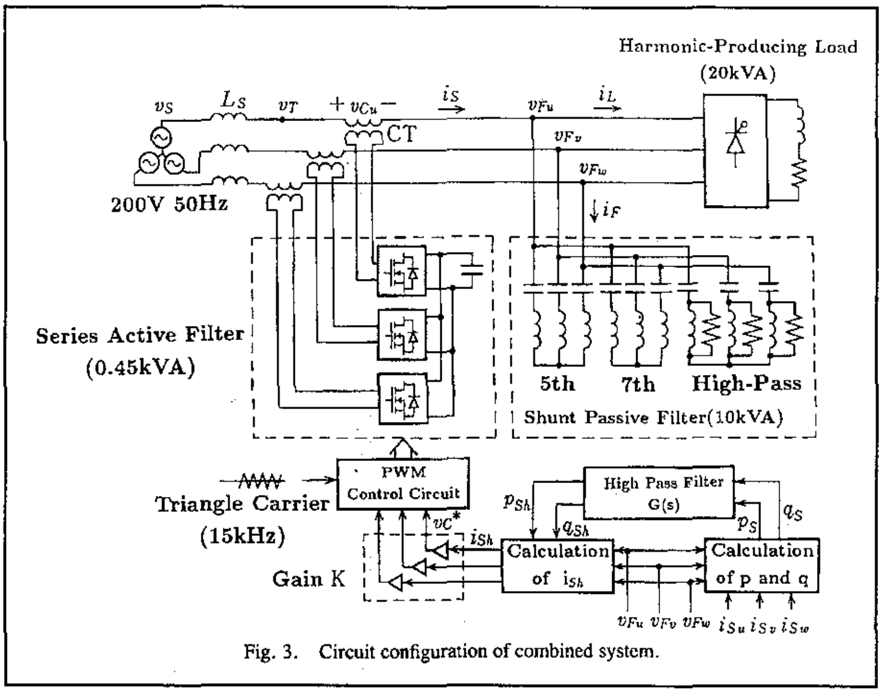


Figure 2.6: The circuit configuration of the series active filter combined with shunt passive filter proposed in [3]

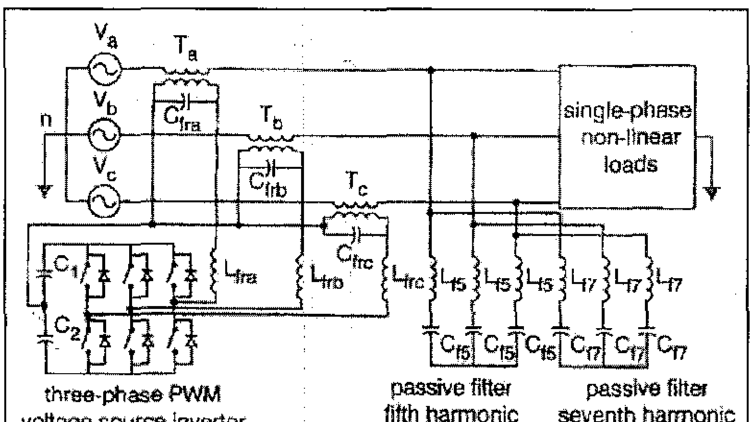


Figure 2.7: The circuit configuration of the series active filter combined with shunt passive filter proposed in [2]

The principle of operation for both configurations is the same but differs in their control scheme for harmonic compensation. The PWM-VSI connected to the circuit in series with the power lines through the single-phase coupling transformer formed the power circuit configuration of the circuit [2, 3, 10]. The three-phase PWM VSI had an advantage over three single phase PMW-VSI because of smaller number of power components required in the circuit which means a lower cost needed [2]. The PWM-VSI is controlled by an adequate control scheme in order to compensate for the current and voltage harmonic [10]. An appropriate voltage waveform is generated based on the line current input and is reflected back into the power line through the coupling transformer to achieve the current harmonic and voltage compensation [2, 3]. The passive filter is connected in parallel to the power line in order to compensate for the higher order of current harmonic which is 5^{th} and 7^{th} harmonic by choosing an appropriate value for each inductor and capacitor value [2, 3, 10].

The shunt-connected passive filter caused the series active filter to operate as an harmonic isolator where the current harmonic is circulating around the passive filter that result in a lower rated series active filter required [3]. Voltage of the same frequency of the current harmonic component that is to be eliminated is generated by the series active filter through its control circuit. Generation of this voltage waveform of the same frequency created a high impedance path to the current harmonics in the power line [10]. This high impedance path will forced the high frequency currents to flow through the passive filter [10]. By using this type of configuration, it can compensate for current harmonics caused by nonlinear loads, voltage unbalances and voltage sags at the load terminal [2]. The limitation encountered in [3] is that the topology is unable to compensate for the load power factor.

2.4.2 Harmonic compensation

The compensation principle of the combined system was derived in per-phase equivalent circuit for simplification [3]. The voltage source PWM inverter is assumed to be an ideal controllable voltage source, $\dot{v}_c$. From the circuit configuration in figure 2.7, the per-phase equivalent circuit is represented as in figure 2.8. $\dot{Z}_F$ is the equivalent impedance of the shunt passive filter which composed of the respective inductance and capacitance to suppress the 5^{th} and 7^{th} harmonic [3]. $\dot{Z}_S$ represent the source impedance, $\dot{V}_S$ is the source voltage comprises of harmonic voltage source, $\dot{V}_{Sh}$ and fundamental component, $\dot{V}_{Sf}$. As comprises of harmonic voltage source, $\dot{V}_{Sh}$ and fundamental component, $\dot{V}_{Sf}$. As describe in the previous section, series active filter is to present zero impedance to external circuit at fundamental frequency and to impose a high resistance K to source or load harmonic [2, 3]. This operation is represented by figure 2.9 and 2.10 respectively by applying the law of superposition to per-phase equivalent circuit.

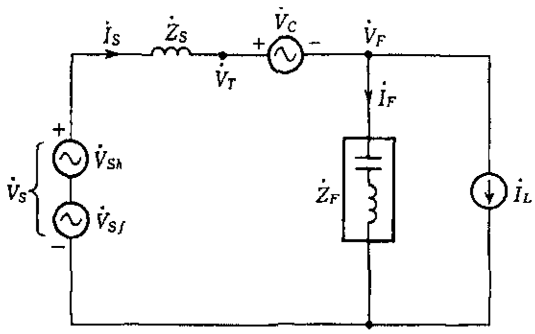


Figure 2.8: Per-phase equivalent circuit of the combined system

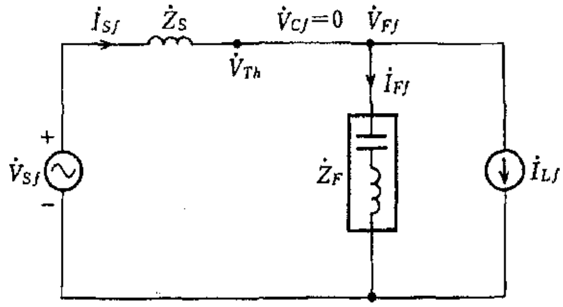


Figure 2.9: Equivalent circuit for fundamental frequency of the combined system

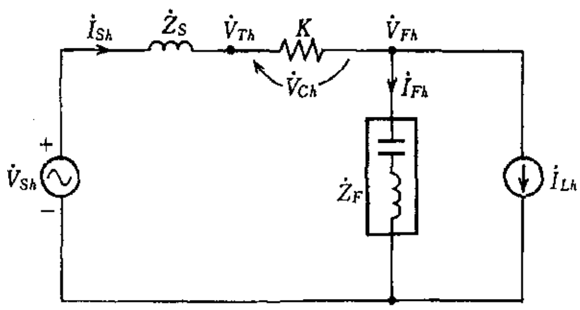


Figure 2.10: Equivalent circuit for harmonic frequencies of the combined system

$\dot{I}_{Lf}$ is the load fundamental current and $\dot{I}_{Lh}$ is the load harmonic current. By looking at the circuit, the series active filter only operates as the harmonic isolator between the source and load and the shunt passive filter behaves as a capacitor for power factor improvement [2, 3, 13]. From figure 2.9, the harmonic current flowing through the source, $\dot{I}_{Sh}$ is given as:

$$\dot{I}_{Sh} = \frac{\dot{Z}_F}{\dot{Z}_S + \dot{Z}_F + K} \cdot \dot{I}_{Lh} + \frac{\dot{V}_{Sh}}{\dot{Z}_S + \dot{Z}_F + K}$$

From the equation above, it can be conclude that for K >> $\dot{Z}_S$ and $\dot{Z}_F$, $\dot{I}_{Sh}$ ≈0 [3]. The first term on the RHS shows that series active filter can eliminate the parallel resonance between shunt passive filter and source impedance and the second term shows that it can prevent the harmonic current produced by source from flowing into the passive filter [3]. The variation in the source impedance will not affect the filtering characteristic of the passive filter provided that K is much larger than source impedance where $\dot{I}_{Sh}$ ≈0 [2, 3].

The output voltage of the series active filter is equal to the harmonic voltage across resistance K, and given by:

$$\dot{V}_C = K\dot{I}_{Sh} = K \cdot \frac{\dot{Z}_F\dot{I}_{Lh} + \dot{V}_{Sh}}{\dot{Z}_S + \dot{Z}_F + K}$$

For the condition K>>$\dot{Z}_S$,$\dot{Z}_F$, $\dot{V}_C$ ≈ $\dot{Z}_F$ $\dot{I}_{Lh}$+$\dot{V}_{Sh}$ [3]. The voltage rating of the series active filter is given as a vector sum of the first term on the right side, which is inversely proportional to the quality factor of the shunt passive filter, and the second term, which is equal to the source harmonic voltage.

The harmonic voltage across the shunt passive filter, $\dot{V}_{Fh}$ is given by:

$$\dot{V}_{Fh} = -\frac{Z_S + K}{\dot{Z}_S + \dot{Z}_F + K} \cdot \dot{Z}_F\dot{I}_L + \frac{Z_F}{\dot{Z}_S + \dot{Z}_F + K} \cdot \dot{V}_{Sh}$$

And for the condition K>>$\dot{Z}_S$,$\dot{Z}_F$, $\dot{V}_{Fh}$ ≈-$\dot{Z}_F$ $\dot{I}_{Lh}$which shows that there are no source harmonic voltage on the load side because it is applies across series active filter [3]. The harmonic compensation principle of the series active filter and shunt passive filter is theoretically explained by the above derivation and the value of K used is usually 1 or 2 for the application of hybrid filter [2, 3].

The filtering characteristic is further elaborated by considering the two conditions of harmonic current flow, the harmonic current flowing from the load to source and the harmonic current flowing from the source to shunt passive filter [3]. In the case of current harmonic flowing from load to source, the load harmonic current divides between the shunt passive filter and the source in proportion of the admittance of the parallel branches and the ratio of the source harmonic current to the load current is given by;

$$\left.\frac{\dot{I}_{Sh}}{\dot{I}_{Lh}}\right|_{\dot{V}_{Sh}=0} = \frac{\dot{Z}_F}{\dot{Z}_S + \dot{Z}_F + K}$$

The voltage source harmonic is assumed to be zero [3]. When the K value is taken to be 1 or 2, which is the case of combined system, the result shows that the distribution factor for all frequencies is reduced [3]. The series active filter act as a damping resistance where no amplification occurs in harmonic current with the sharpest filtering of 5th, 7th and higher harmonics is obtained in K=2 [3]. For the compensation of harmonic current flowing from the source to shunt active filter, the load current harmonic is assumed to be zero and the source harmonic current is:

$$\dot{I}_{Sh}\Big|_{\dot{I}_{Lh}=0} = \frac{\dot{V}_{Sh}}{\dot{Z}_S + \dot{Z}_F + K} = \frac{\dot{V}_{Sh}}{\dot{Z}_1}$$

Where $\dot{Z}_1 = \dot{Z}_S + \dot{Z}_F + K$ [3]. In the case of combined system, where K=1 or 2, the ratio of $\dot{Z}_1$ to the rated impedance increases for all frequencies and there is no harmonic current flows into the source or the shunt passive filter as the series active filter act as a blocking resistance [3]. The compensation characteristic is closely related to the control scheme of the circuit. The compensation for the voltage unbalance was introduced in addition to the existing system [2]. Furthermore, the compensation characteristic for fluctuating load was extensively studied [13]. These compensations and their control schemes are elaborated in the following section.

2.4.3 Control Scheme

The objective of the control circuit applied to the series active filter is for it to present zero impedance for the fundamental frequency component and imposed a pure resistance for the harmonic frequency component as described in the harmonic compensation above [2, 3]. In order to do this, the reference output voltage must be given by:

$$v_c^* = \mathrm{K} \cdot i_{\mathrm{Sh}}$$

Where i_{Sh} is the source harmonic current that need to be calculated from the detection of source current on the line between CT and the passive filter. Referring to [2] and [3], the calculation of i_{Sh} is done by applying instantaneous real and imaginary power theory, the so-called *"p-q* theory" developed by H. Akagi *et al* [3]. The block diagram of control circuit proposed in [3] is shown in figure 2.11 [13].

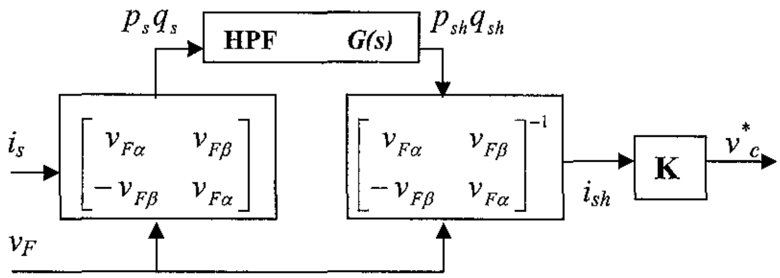


Figure 2.11: Control circuit for the series active filter

According to the instantaneous real and imaginary power theory, the current source harmonic, i_{Sh} is calculated by using real and imaginary power, p_s and q_s [13]. The source current and the line voltage is first transferred into the stationary frame, $\alpha\beta$ by using these relationship [3, 13]:

$$\begin{bmatrix} v_{L\alpha} \\ v_{L\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix}$$

$$\begin{bmatrix} i_{S\alpha} \\ i_{S\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} i_{S1} \\ i_{S2} \\ i_{S3} \end{bmatrix}$$

The instantaneous real and imaginary power is then obtained by multiplying the line voltage and source current in $\alpha\beta$ frame as follows [3, 13]:

$$\begin{bmatrix} p_S \\ q_S \end{bmatrix} = \begin{bmatrix} v_{F\alpha} & v_{F\beta} \\ -v_{F\beta} & v_{F\alpha} \end{bmatrix} \cdot \begin{bmatrix} i_{S\alpha} \\ i_{S\beta} \end{bmatrix}$$

The dimension for p_s and q_s are not watt or var since it is an instantaneous value. Using Laplace transformation, the harmonic components of p_s and q_s are extracted by applying a high pass filter (HPF), H(s) as can be seen in the figure 2.11 [13].

$$\begin{bmatrix} P_{Sh} \\ Q_{Sh} \end{bmatrix} = H(s) \begin{bmatrix} P_S \\ Q_S \end{bmatrix}$$

with $H(s) = s/(s + \omega_c)$; ω_c is the HPF cut-off frequency.

The cut-off frequency is 35 Hz by taking into account the transient states characteristic [3]. The current source harmonic in the $\alpha\beta$ frame is then calculated as follows and the series active filter voltage is given by [3, 13]:

$$\begin{bmatrix} i_{Sh\alpha} \\ i_{Sh\beta} \end{bmatrix} = \begin{bmatrix} v_{F\alpha} & v_{F\beta} \\ -v_{F\beta} & v_{F\alpha} \end{bmatrix}^{-1} \begin{bmatrix} p_{Sh} \\ q_{Sh} \end{bmatrix}$$

$$\begin{bmatrix} v_{C\alpha} \\ v_{C\beta} \end{bmatrix} = K \begin{bmatrix} i_{Sh\alpha} \\ i_{Sh\beta} \end{bmatrix}$$

Harmonic source current in $\alpha\beta$ frame, $i_{Sh\alpha}$ and $i_{Sh\beta}$ are then transformed back into line current with the following transformation [3]:

$$\begin{bmatrix} i_{Sh1} \\ i_{Sh2} \\ i_{Sh3} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_{F\alpha} & v_{F\beta} \\ -v_{F\beta} & v_{F\alpha} \end{bmatrix}^{-1} \begin{bmatrix} p_{sh} \\ q_{sh} \end{bmatrix}$$

These line harmonic source currents, i_{Sh1}, i_{Sh2} and i_{Sh3} are multiplied with a constant K to get the reference output voltage, v_c [2, 3]. The reference output voltage waveform obtained is compared with the triangle carrier waveform with a fixed frequency to produce the PWM switching patterns [3]. Here the frequency of the triangle carrier is 15 kHz [3]. Series active filter operates as a controllable voltage source; hence a voltage-source PWM inverter is suitable for the series active filter rather than a current-source PWM inverter [3].

Compensation of voltage unbalance

Additional compensation characteristic was introduced in order to be able to compensate voltage unbalance along with the current harmonics [2].

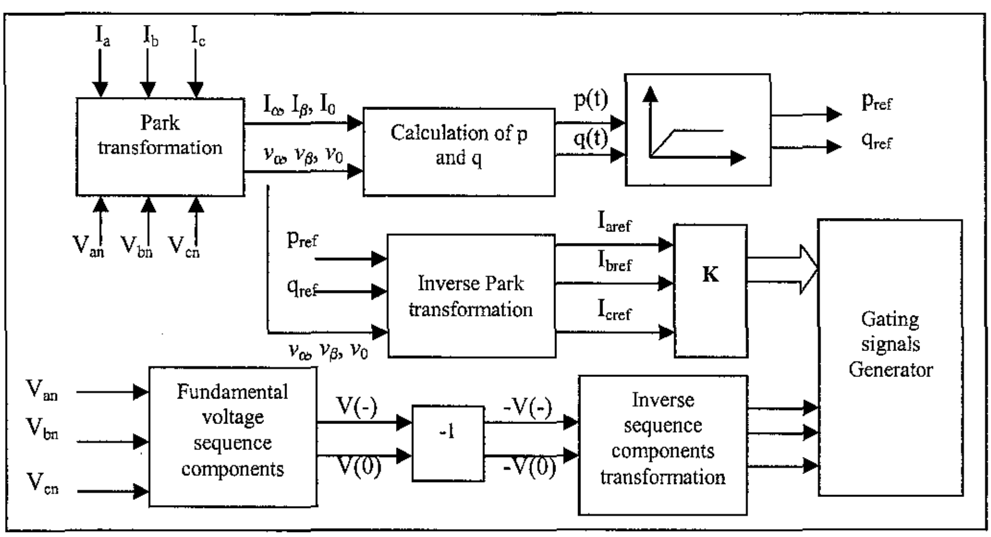


Figure 2.12: Control circuit for the combined system to compensate voltage unbalanced and current harmonics [2]

Figure 2.12 shows the control circuit of the combined system to compensate for voltage unbalance and current harmonics as well. Voltage unbalance is compensated by calculating the negative and zero sequence fundamental components of the source voltage [2]. In order to calculate the voltage reference signal, the zero, positive and negative sequence of the voltage is obtained by following equation [2]:

$$\begin{pmatrix} v_{a0} \\ v_{a1} \\ v_{a2} \end{pmatrix} = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix} \cdot \begin{pmatrix} v_a \\ v_b \\ v_c \end{pmatrix}$$

Where v_a, v_b and v_c is the phase to neutral voltage before the coupling transformer and a is equal to $1\angle 120^o$. The positive sequence component, v_{a1} is made zero and the inverse fortescue transformation is applied to the rest as follows:

$$\begin{pmatrix} v_{refa} \\ v_{refb} \\ v_{refc} \end{pmatrix} = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{pmatrix} \cdot \begin{pmatrix} -v_{a0} \\ 0 \\ -v_{a2} \end{pmatrix}$$

The reference voltage signal is obtained from here and the series active filter can only compensate the voltage unbalance and not the voltage regulation [2, 10]. Since the zero sequence current is generated by the source voltage unbalance and the voltage unbalance is compensated by using the above method, the magnitude of the fundamental component of the line current is significantly reduced [2]. Thus, the line current resulting from the voltage unbalance is needed to be compensated by taken into account the zero sequence harmonic components. For current harmonic compensation, the control scheme is the same as explained in previous section since the voltage and current control scheme is independent [2, 3]. The general equation of the reference of the PWM-VSI became as [2, 10]:

$$\begin{pmatrix} v_{refa} \\ v_{refb} \\ v_{refc} \end{pmatrix} = K_1 \left[\sqrt{\frac{2}{3}} \cdot \begin{pmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{pmatrix} \begin{pmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\beta \end{pmatrix}^{-1} \begin{pmatrix} p_{ref} \\ q_{ref} \end{pmatrix} + \frac{1}{\sqrt{3}} \begin{pmatrix} i_{0ref} \\ i_{0ref} \\ i_{0ref} \end{pmatrix} \right] + K_2 \left[\frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{pmatrix} \cdot \begin{pmatrix} -v_{a0} \\ 0 \\ -v_{a2} \end{pmatrix} \right]$$

Where K_1 is the gain of the series transformer which defines the magnitude of the impedance for high current components K_2 is the degree of the compensation for voltage unbalance [2]. The control circuit of the compensation shown in figure 2.12 and the calculated voltage reference signal only allow the flow of the reactive power between the series active filter and compensated system. Thus, by using this control scheme, it is unable to compensate for voltage regulation [2, 10].

Compensation of the fluctuating load

The method proposed in [3] is able to compensate the harmonic effectively for symmetrical load. Figure 2.13 shows the positive and negative sequence compensation characteristic when using the first order HPF. The problem arises for compensating the harmonic of fluctuating loads where the transient performance deteriorates [13]. This is because the fluctuating load results in sub and superharmonic currents near the fundamental frequency. These harmonics in the source current appear as low-frequency components in their instantaneous powers p_s and q_s, which make it difficult to extract the harmonic components p_{Sh} and q_{Sh} [13].

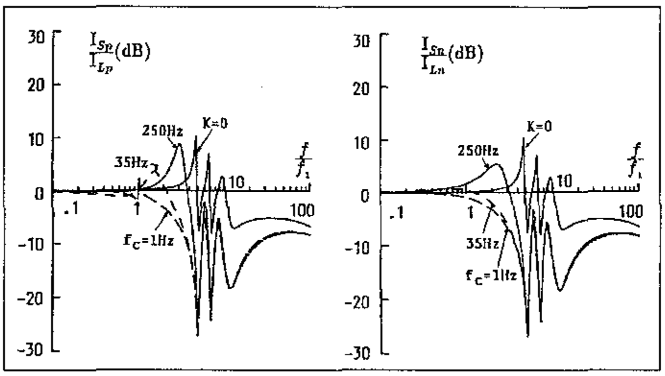


Figure 2.13: The positive and negative sequence compensation characteristic for first order HPF

The cut-off frequency, f_c of these loads will be smaller and this caused the compensation characteristic to deviate from the characteristic shown in figure 2.13 [3]. The harmonic current that contain sub and superharmonic near the fundamental frequency component cannot be notched effectively by a low cut-off frequency of first order HPF, H(s) [3, 13]. The voltage across the series active filter, v_c becomes large and caused the current transformer to saturate and the PWM VSI to overcurrent and overvoltage because the voltage rating is very small [13].

In order to overcome this problem, a new control method is proposed as shown in figure 2.14 [13]. In the proposed control method to encounter the fluctuating load, the shunt passive filter current and the load current are detected [13]. The instantaneous power is calculated respectively, p_L, q_L and p_F, q_F and the harmonic components is extracted by the $G_1(s)$ and $G_2(s)$ respectively [13]. $G_1(s)$ is the first order HPF with cut-off frequency f_{c1} and $G_2(s)$ is the second order Butterwort-type HPF with cut-off frequency of f_{c2}. The source current, I_s is given by [13]:

$$
\begin{aligned}
I_S(s) = {} & [Z_F U + K(G_1(s) - G_2(s))] \cdot [(Z_S + Z_F)U + KG_1(s)]^{-1} \cdot I_L(s) \\
& + [(Z_S + Z_F)U + KG_1(s)]^{-1} \cdot V_S(s)
\end{aligned}
$$

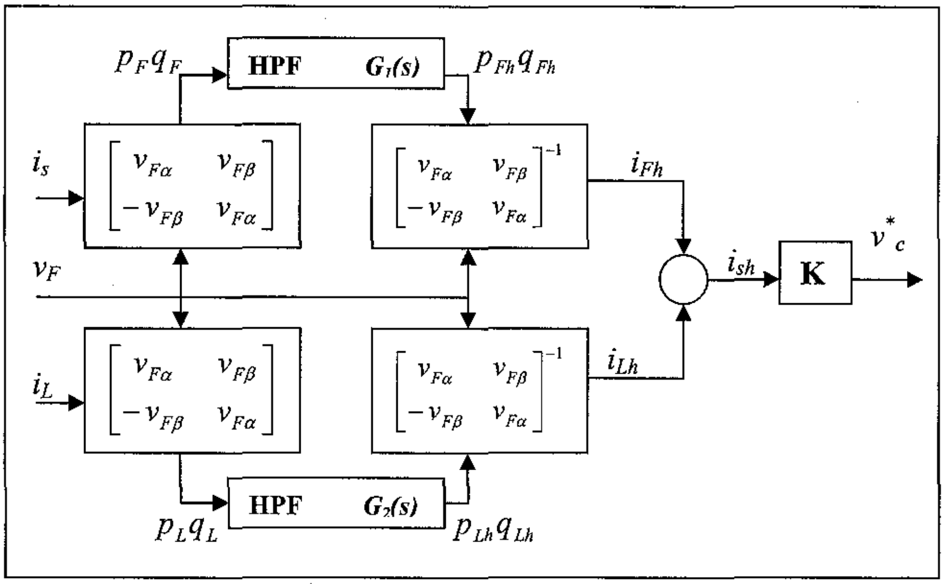


Figure 2.14: Block diagram of the new control method.

The new control method has the same characteristics of the source $V_s(s)$ but different characteristics of the load $I_L(s)$ from the method proposed in [3]. However, the operating principle is quite the same. The sub and superharmonics near the fundamental frequency can be effectively notched by second-order HPF $G_2(s)$ [3]. Since the sub and superharmonics in shunt passive filter are very small compared with the load current, the sub and superharmonic voltage, ΔV_C can be considerably reduced [13]. The stability of the system is only dependent on $G_1(s)$ and K, thus its stability maintained as in previous control method. The compensation characteristic of the new control method is shown in figure 2.15 where it can be seen the characteristic near fundamental frequency was improved [13]. Figure 2.16 shows the experimental result when the new control method was applied to the system which indicates the improvement in the reduction of the output voltage across the series active filter [13].

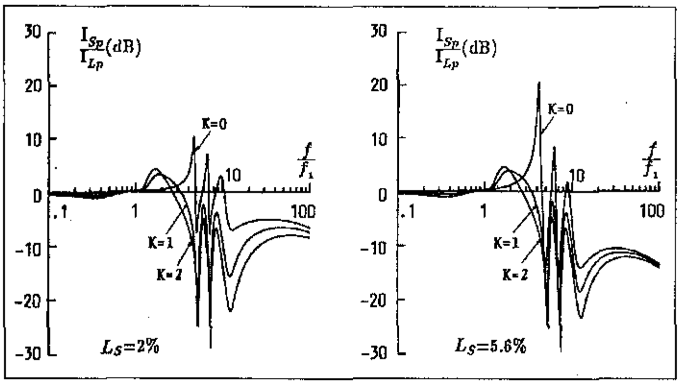


Figure 2.15: The compensation characteristic of the combined system of series active filter and shunt passive filter with new control method

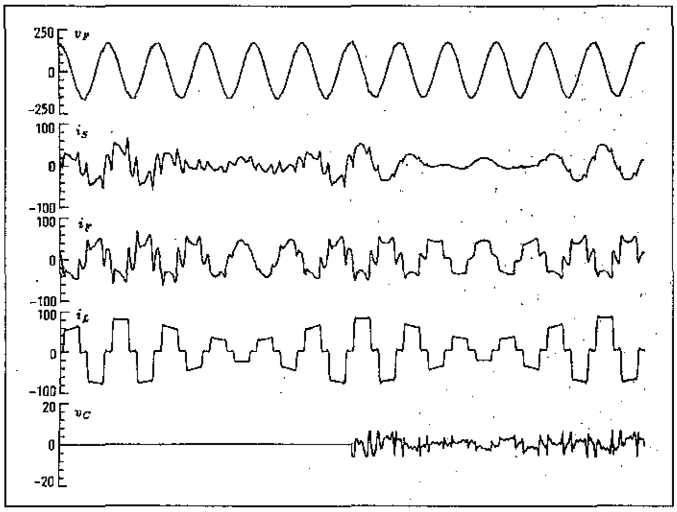


Figure 2.16: The experimental result of the combined system of series active filter and shunt passive filter with new control method

2.4.4 Power circuit

Shunt Passive filter

One of the important components in the circuit configuration is the passive filter connected in parallel to the power line in order to compensate for the load current harmonic. Since the passive filter connected together with the series active filter which acts as a harmonic isolator, the design can be insensitive to the system impedance and eliminates the possibility of filter overloading due to supply voltage harmonic [10]. Passive filter is tuned to the dominant load current harmonic which are the lower order harmonic and also can be designed to the correct the load displacement power factor [13]. Ambient harmonics generated elsewhere on the ac system including the harmonics from the ac source do not sink into the passive filter

[13]. Figure 2.17 shows the single-phase equivalent circuit of passive LC filter in parallel with the nonlinear current source and to the power line [10].

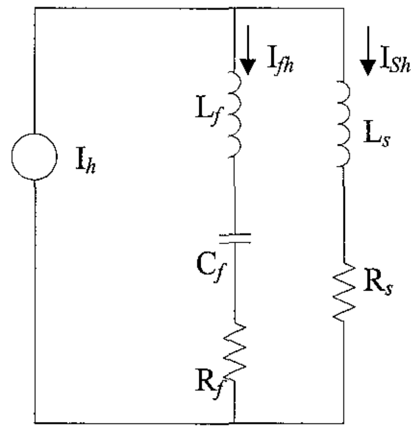


Figure 2.17: Single-phase equivalent circuit of passive filter in parallel with nonlinear load

The harmonic current flowing through the passive filter is given by [10]:

$$\dot{I}_{Fh} = \frac{Z_S}{Z_S + Z_f} I_h ,$$

and the current component flowing through the source is given by [10]:

$$\dot{I}_{Sh} = \frac{Z_f}{Z_S + Z_f} I_h$$

The passive filter band width is defined by the upper and lower cutoff frequency where the filter current gain is -3dB (or 0.707) as indicated by figure 2.18 [10]

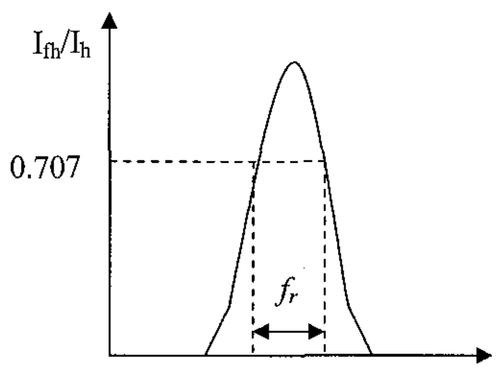


Figure 2.18: Passive filter bandwidth

The inductive reactance of the passive filter is equal to the capacitive reactance of the filter at the resonant frequency, where [10]:

$$2\pi f_r L = \frac{1}{2\pi f_r C},$$

Therefore, the resonant frequency of the filter is given by [10]:

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

At resonant frequency, the passive filter magnitude is equal to the resistance, thus when the resistance is zero, the filter will be short circuit. The quality, Q of the passive filter is defined as [10]:

$$Q = \frac{\omega_n L}{R}$$

The concern in the selection of the passive filters components is when the small kvar passive filter required in the event of the diode rectifier type of loads connected. It is difficult to achieve the required tuning to absorb significant percentage of the load harmonic currents [3, 10]. For this type of application, the passive filter cannot be tuned exactly to the harmonic frequencies because they can be overloaded due to the system voltage distortion and current harmonics [1]. Generally, the values for the constant passive filter used are show in the table 2.3 and 2.4 respectively:

Table 2.3: The circuit constant of inductor and capacitor in [2]

Harmonics	Inductor	Capacitor	Quality
Fifth	L = 1.20 mH	C = 340μF	Q = 14
Seventh	L = 1.20 mH	C = 170μF	Q = 14

Table 2.4: The circuit constant of inductor and capacitor in [3]

Harmonics	Inductor	Capacitor
Fifth	L = 6.22 mH	C = 65μF
Seventh	L = 3.17 mH	C = 65μF

Secondary Ripple Filter

The secondary ripple factor depends mainly on the coupling transformer turn ratio and on the current modulator used to generate the inverter gating signal [10]. The design was proposed by Akagi [3] and also implemented in [2]. Figure 2.19 shows the single phase equivalent circuit of the inverter output ripple, V_{rip}.

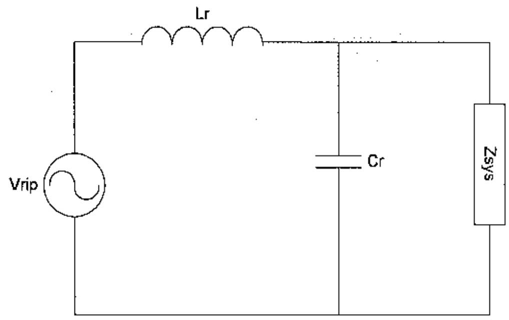


Figure 2.19: The single-phase equivalent circuit as seen from the inverter

The selection of the L_r and C_r value is done not to exceed the burden of coupling transformer and must be designed for the carrier frequency of the PWM-VSI [2, 10]. Z_{sys} is the amplitude of the sum of shunt passive filter impedance and system impedance which are seen from the secondary of the coupling transformer and must be known in order to determine the L_r and C_r value [2]. It is given by:

$$Z_{sys(\text{secondary})} = (n_2/n_1)^2\, Z_{sys(\text{primary})}$$

Where n_2/n_1 is the turn ration of coupling transformer and always be taken as 20 and $Z_{sys(\text{primary})}$ is the sum of shunt passive filter impedance and source impedance [2,10]. In selection of the carrier frequency, there are design criteria that must be satisfied [2]:

(i) $X_{Cr} << X_{Lr}$: in order to ensure that most of the inverter output voltage will drop across the L_r at carrier frequency

(ii) X_{Cr} and $X_{Lr} << Z_{sys}$: in order to ensure that the voltage divider is between L_r and C_r.

The relationship of the Z_{sys} to the L_r and C_r can be shown as follows for the case where the switching ripple frequency is two times switching frequency, f_s [2]:

$$Z_{sys} >> 1/\{2\pi(2f_s)C_r\} \quad \text{and} \quad Z_{sys} << 2\pi(2f_s)L_r$$

The voltage reflected in the primary winding of the coupling transformer has the same waveform of that the voltage across the filter capacitor [2, 10]. The output voltage of the inverter must be almost equal to the voltage across C_r for low frequency component while for high frequency components; voltage at the capacitor is almost zero since most of the output voltage drop across L_r [2]. The ripple filter connected to the series active filter avoid the induction of the high frequency ripple voltage generated by PWM inverter switching pattern at the primary winding of coupling transformer since the ripple voltage was largely reduced [2, 10].

2.5 INSTANTANEOUS ACTIVE AND REACTIVE POWER OR 'P-Q' METHOD

The instantaneous real active and reactive power or so-called 'p-q' theory was proposed by Akagi to generate the reference current template for active filter [20]. In that technique the real and imaginary powers are calculated, both of them with dc and ac components [15]. The dc components that are related to the fundamental frequency are extracted by means of conventional filters. The ac components resting are related to the harmonic content of the load currents and they are used to generate the reference template of the compensation currents [15, 20].

In this technique the instantaneous active and reactive power, p and q of the nonlinear load is calculated by multiplying the main voltage, v_l with the nonlinear load current, i_d in a stationary reference frame ($\alpha\beta$) [3, 5, 20] . The main voltage, v_l and load current is given by:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix}$$

$$\begin{bmatrix} i_{l\alpha} \\ i_{l\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} i_{l1} \\ i_{l2} \\ i_{l3} \end{bmatrix}$$

Where v_1, v_2, v_3 and i_1, i_2, i_3 is respective line voltage and current [5]. Zero voltage component of voltage and current is assumed to be zero since absence of neutral wire is considered. The instantaneous power, p and reactive power, q is given by [5]:

$$\begin{bmatrix} p_l \\ q_l \end{bmatrix} = \begin{bmatrix} u_\alpha & u_\beta \\ u_\beta & -u_\alpha \end{bmatrix} \cdot \begin{bmatrix} i_{l\alpha} \\ i_{l\beta} \end{bmatrix}$$

Resulting p and q composed of the oscillatory or ac and average or dc component.

$$p_l = \tilde{p}_l + P_l \quad \text{and} \quad q_l = \tilde{q}_l + Q_l$$

Under balanced and sinusoidal supply voltage condition, the dc component of real power is related to the first harmonic current of the positive sequence and ac component represent all higher order current harmonic including first harmonic current of negative sequence [5].

The ac component of real and reactive power is then filtered through high pass filter to eliminate the dc component and leave the ac component, p_{ac} and q_{ac} to be compensated. From these ac power components, the compensation current is obtained by inverting the matrix above [5];

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \frac{1}{u_\alpha^2 + u_\beta^2} \begin{bmatrix} u_\alpha & u_\beta \\ u_\beta & -u_\alpha \end{bmatrix} \cdot \begin{bmatrix} p_c \\ q_c \end{bmatrix}$$

$$\begin{bmatrix} i_{c1} \\ i_{c2} \\ i_{c3} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}^T \cdot \begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix}$$

For the implementation in series active power filter, SAPF the instantaneous power component is filtered using low pass filter and dc component is given by [3]:

$$\begin{bmatrix} P_{Sh} \\ Q_{Sh} \end{bmatrix} = H(s) \begin{bmatrix} P_S \\ Q_S \end{bmatrix}$$

This method have the drawback of being affected by the presence of harmonics in the voltage and of uses of conventional filtering, decreasing its dynamic response. The method is very efficient for balanced three-phase loads [3, 15].

2.6 INSTANTANEOUS ACTIVE AND REACTIVE CURRENT COMPONENT (I_D-I_Q) METHOD

The development of dq0 transformation was carried out by R.E Doherty, C.A Nickle, R.H Park, and their associates in United States based on the idea of 'two reaction method' [16]. The transformation is applied in resolving the synchronous-machine armature quantities into two rotating component. The concept is to resolve the synchronous-machine armature quantities into two rotating components, one is aligned with the field-winding axis or the direct axis component and one is quadrature with the field winding axis, or the quadrature-axis component [16]. This concept stems from the fact that although each of the stator phases sees a time-varying inductance due to the saliency of the rotor, the quantities rotate with the rotor and hence see constant magnetic path [13]. Later, this principle was used as a basis for transformation in power electronics field where the voltage and current produces from the generator is to be separated from its axis. The work on i_d-i_q method was proposed in [5] as an alternative of 'p-q theory'. In this method, the voltage and current is transformed from the stationary frame, α-β axis to rotating frame, d-q axis [5].

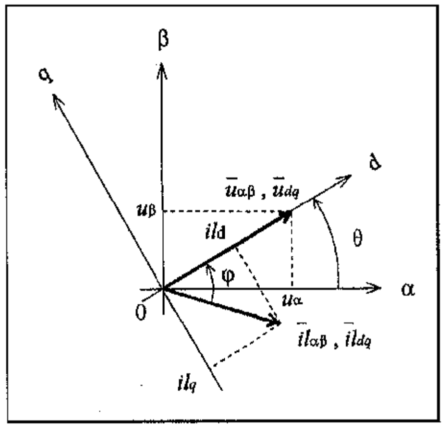


Figure 2.20: Voltage and current space vectors in the stationary and rotating frames

In the i_d-i_q method, the active filter current, i_{ci} are obtained from the instantaneous active, i_{ld} and reactive current components, i_{lq} of the nonlinear load [5]. The source voltages and the nonlinear load currents in α-β stationary frame are calculated as in the equation of the p-q method. However, the load current components are derived from a synchronous reference frame based on the Park transformation, where represents the instantaneous voltage vector angle [5]

$$\begin{bmatrix} i_{ld} \\ i_{lq} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \cdot \begin{bmatrix} i_{l\alpha} \\ i_{l\beta} \end{bmatrix}, \; \theta = \tan^{-1} \frac{u_\beta}{u_\alpha}$$

Figure 2.20 shows the voltage and current space vectors in the stationary and rotating frames [5]. The angle is proportional with time under balanced and sinusoidal source voltage condition and it is sensitive to voltage harmonics and unbalance [5]. The active and reactive current in rotating frame is given by:

$$\begin{bmatrix} i_{ld} \\ i_{lq} \end{bmatrix} = \frac{1}{\sqrt{u_\alpha^2 + u_\beta^2}} \cdot \begin{bmatrix} u_\alpha & u_\beta \\ u_\beta & -u_\alpha \end{bmatrix} \cdot \begin{bmatrix} i_{l\alpha} \\ i_{l\beta} \end{bmatrix}$$

These currents, il_d and il_q comprise of ac and dc component and can be decomposed into each component by filtering through the HPF. The first harmonic current of positive sequence is transformed to dc quantities and all higher order current harmonics including first harmonic current of negative sequence are transformed to ac quantities [5]. The assumption is valid under balanced and sinusoidal main voltage. After filtering out the dc component, the current that need to be compensated now are, $il_{cd} = -\tilde{l}_d$ and $il_{cq} = \tilde{l}_q$. The converter current in α-β coordinate system is given by [5]:

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \frac{1}{\sqrt{u_\alpha^2 + u_\beta^2}} \cdot \begin{bmatrix} u_\alpha & -u_\beta \\ u_\beta & u_\alpha \end{bmatrix} \cdot \begin{bmatrix} i_{cd} \\ i_{cq} \end{bmatrix}$$

Soares et al [5] had presented the comparison between the two methods, p-q and i_d-i_q method. It was shown that both methods under balanced and sinusoidal voltage conditions will have the same performance [5]. However, under other voltage condition such as distorted supply voltage, the ac and dc power component for p-q method will be affected by voltage harmonic and unbalanced voltage condition, thus harmonic cannot be eliminated completely [5]. The i_d-i_q method under unbalanced and non-sinusoidal voltage condition gives a better performance in eliminating harmonic as compared to p-q method. Theoretically, this can be shown by the equivalent compensation power for both methods below [5]:

$$\begin{bmatrix} p_{c1} \\ q_{c1} \end{bmatrix} = -U_d \cdot \begin{bmatrix} \tilde{i}_{ld} \\ -\tilde{i}_{lq} \end{bmatrix} - \tilde{u}_d \cdot \left(\begin{bmatrix} I_{ld} \\ -I_{lq} \end{bmatrix} + \begin{bmatrix} \tilde{i}_{ld} \\ -\tilde{i}_{lq} \end{bmatrix} \right)$$

$$\begin{bmatrix} p_{c2} \\ q_{c2} \end{bmatrix} = -\left(U_d + \tilde{u}_d\right) \cdot \begin{bmatrix} \tilde{i}_{ld} \\ -\tilde{i}_{lq} \end{bmatrix}$$

The additional disturbance for p-q method under unbalance voltage condition is clearly shown by the difference of the two expressions that degrade its performance [5]. In addition, the performance of p-q method will also affected if the ac component of the voltage and current contain same order harmonic where it result in additional dc component. The simulation to verify the above condition had gives the result as expected [5]:

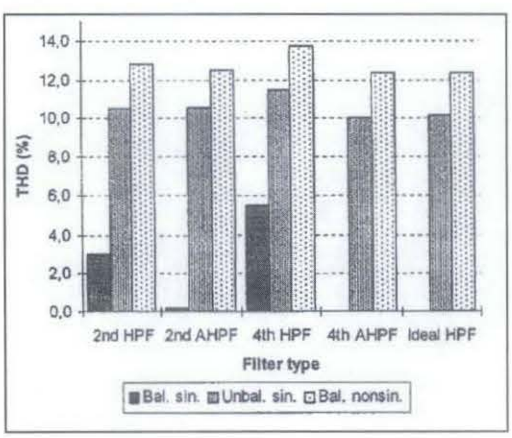


Figure 2.21: p-q method

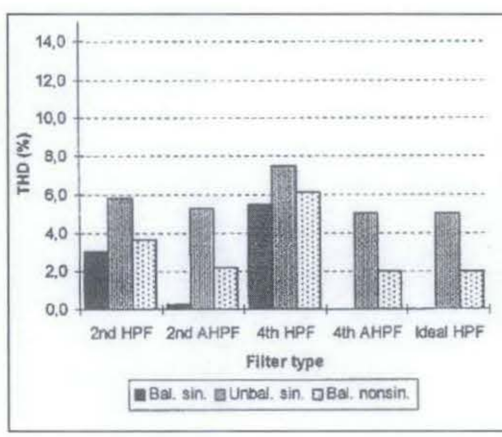


Figure 2.22: i_d-i_q method

Figure 2.21 and 2.22 shows the performance of the p-q and i_d-i_q method under balanced, unbalance sinusoidal and balanced sinusoidal main voltage for different order of HPF. The result had confirmed that the performance of i_d-i_q method is better in unbalanced sinusoidal and balanced sinusoidal.

2.7 Summary of Literature Review

Shunt passive filter was introduced and have been widely used in early days. However, with the advance of technology nowadays, shunt passive filter is not capable of compensating harmonics in power network effectively. Hence, shunt active filter and series active filter were developed. A lot of attention was given to shunt active filter and it is more favorable as compared with series active filter because of its effectiveness in compensating current harmonics. Nevertheless, the increasing usage of diode rectifier in industries which produce a harmonic source voltage type had raised an attention toward series active filter. Shunt active filter is found to be less effective in compensating this type of harmonic. The implementation of series active filter is mainly used to ensure a sinusoidal voltage waveform from the supply. However, its performance can be improved by combining it with the shunt passive filter which enables it to compensate the current harmonics as well. This is called the hybrid filter. The advantage of this type of filter is that the availability of the shunt passive filter in power network makes it easier to implement and the series active filter is only use a small kva rating which minimized the cost. Even though there are not many papers discussing on this type of filter but the student had chosen to focus the study on this type of filter with emphasizing on the control method used. There are two types of control method that are widely use, the p-q method and i_d-i_q method. In shunt active filter, both methods have been implemented and it was shown that i_d-i_q method gives a more favorable result. But, for a combination of series active filter and shunt passive filter, studies have only implemented the p-q method. Thus, the student is intent to implement the i_d-i_q method on this type of filter and comparing the result obtained for both methods.

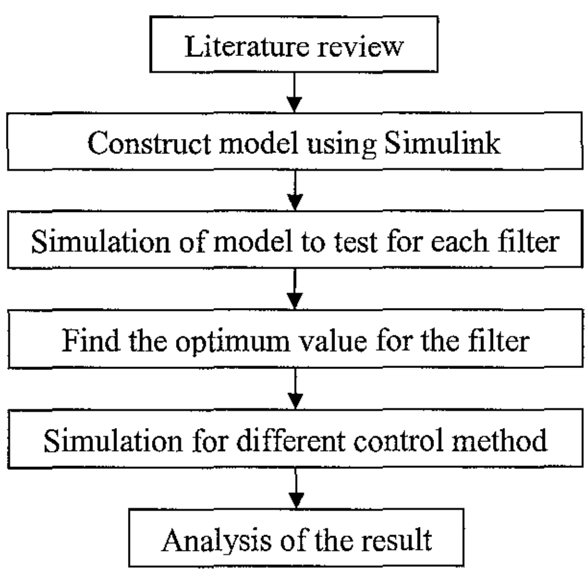
CHAPTER 3

PROJECT WORK

3.0 PROJECT WORK

This project is divided into several phases. For the first phase, a theoretical study of the type of filter and the combination of series active filter and shunt passive filter is done. The development of the filter and its operation is researched into. From the finding, the model of the hybrid filter is developed using MATLAB simulink. The development of the model is done in several stages to examine the role of each filter involved which are shunt passive filter, series active filter and the two operated together. After the constructed model gives a satisfied result, the next phase is to perform the comparison study between using two different control methods that is an instantaneous active and reactive power, p-q method and an instantaneous active and reactive current method, i_d-i_q method.

The model using these types of control is constructed and the result for three different type of supply source condition is investigated. For each of simulated model, the input line current and output line current is monitored and the THD of the waveform is calculated to perceive its quality. The project work is summarized in the chart followed and the details are discussed in the next section. There are some important part of the filter that will be explained in depth which is the selection of shunt passive, the harmonic compensation scheme and the different between the p-q and i_d-i_q method.



3.1 DEVELOPMENT OF THE MODEL

The model developed in this project is chosen for a supply system to a thyristor converter with the dc voltage of 220 V and dc current of 30 A. The thyristor converter is used to provide the harmonic voltage source type to the circuit. The system of a low voltage and current is used because of the feasibility to implement it in laboratory experiment and also to be able to compare the result with the existing result obtained in research paper. The source inductance of 0.4mH is put in the circuit to make it more similar to a real system since there is always an inductance source from the normal supply. The supply source of the simulated circuit is three phase supply with 200 V rms. As described in the previous section, in order to verify the role played by each of the filter, the models developed are divided into several parts before applying the different control method as proposed.

The model was first simulated without any of the filter and the input current and output current is monitored. It is then simulated with shunt passive filter acting alone. The shunt passive filter used comprises of a fifth and seventh harmonic filter only since these are the highest harmonic that usually exist in the system. The selection of the capacitor and inductor value is done by a calculation shown in the next section. The circuit is shown in figure 3.1. The third simulated model is the first circuit with a series active filter acting alone. The filter is connected through the coupling transformer with 20:1 turn ratio, nominal power of 20 000 VA, and the magnetization resistance and reactance is set to 300. The three phase PWM-voltage source inverter is used for this filter to inject a high resistance needed in the circuit. The PWM-VSI is controlled by a power control circuit that taken the harmonic of the line current as its modulating signal. The control scheme in order to obtain the harmonic current will be discussed further in next section. Figure 3.2 shows the simulated circuit.

After each of the filter is tested for operating alone, both of them is combined in one system. This model of series active power filter with shunt passive filter developed is based on the system proposed by [2]. All the circuit value is remain the same as well as for the shunt passive filter and series active filter. Figure 3.3 shows the connection of the system. For every simulation, the input line current and its output were monitored and the THD of each was measured. The result is analyzed from the input and output line current waveform and its THD result. All the simplified circuit of each case is shown below in respective order. For each of the model, there are two cases for which they are tested; the first is where source inductance is set to 0.4mH and the second is 0.6mH.

The simulation is extended to test for a different control scheme for the combined filter. The active filter for the first model used the instantaneous active and reactive power, p-q method as proposed by [2] as shown in the figure 3.3. The second model is where the active filter used the instantaneous active and reactive current or i_d-i_q method as the control scheme which has been proposed by [13]. Figure 3.4 shows the simplified model in MATLAB Simulink. For each of the model, the source inductance was set to 0.4mH and other values remain the same as before. They are simulated for three different supply voltage conditions, which are a balanced normal sinusoidal supply, an unbalanced sinusoidal supply and a balanced non-sinusoidal supply. The normal sinusoidal supply is 200 V_{rms} and the unbalanced supply for phase B and C with 30° apart. For the balanced non-sinusoidal supply, which represent the harmonic insertion in the system, voltage magnitude of 20V is set to each phases at 350 Hz. The waveform obtained for each of cases simulated is monitored and measured to analyze the performance of the different control scheme applied to the combination of series active filter and shunt passive filter.

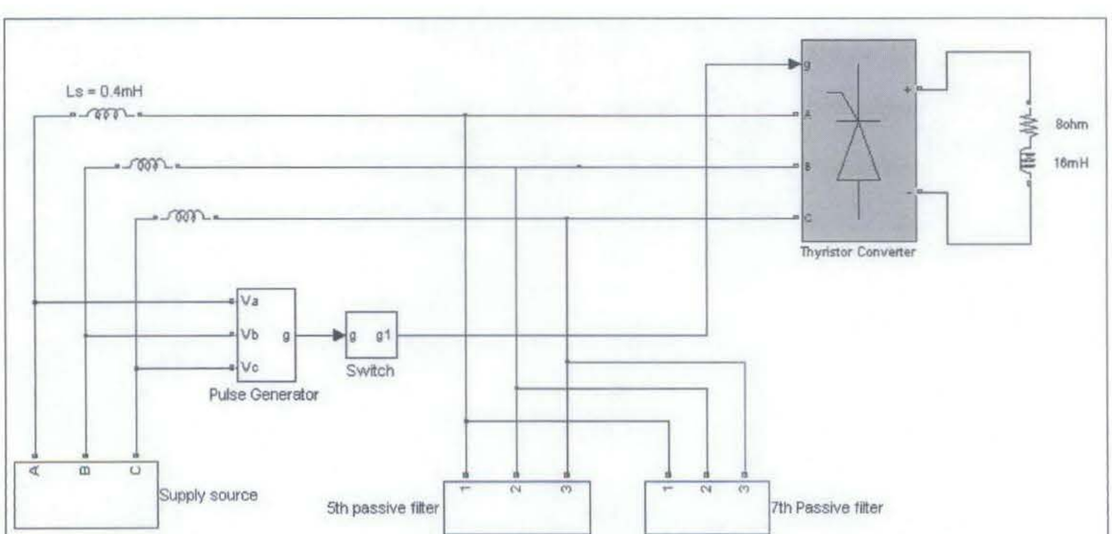


Figure 3.1: A thyristor converter circuit with shunt passive filter

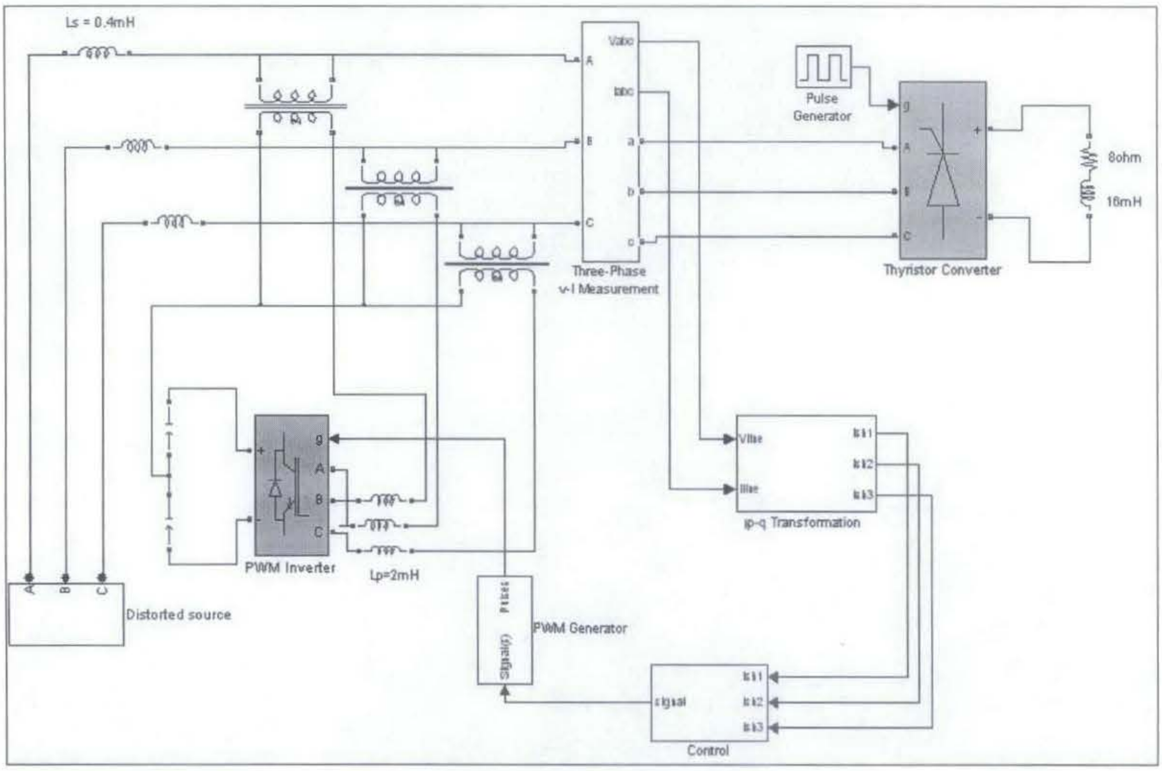


Figure 3.2: A thyristor converter circuit with series active filter

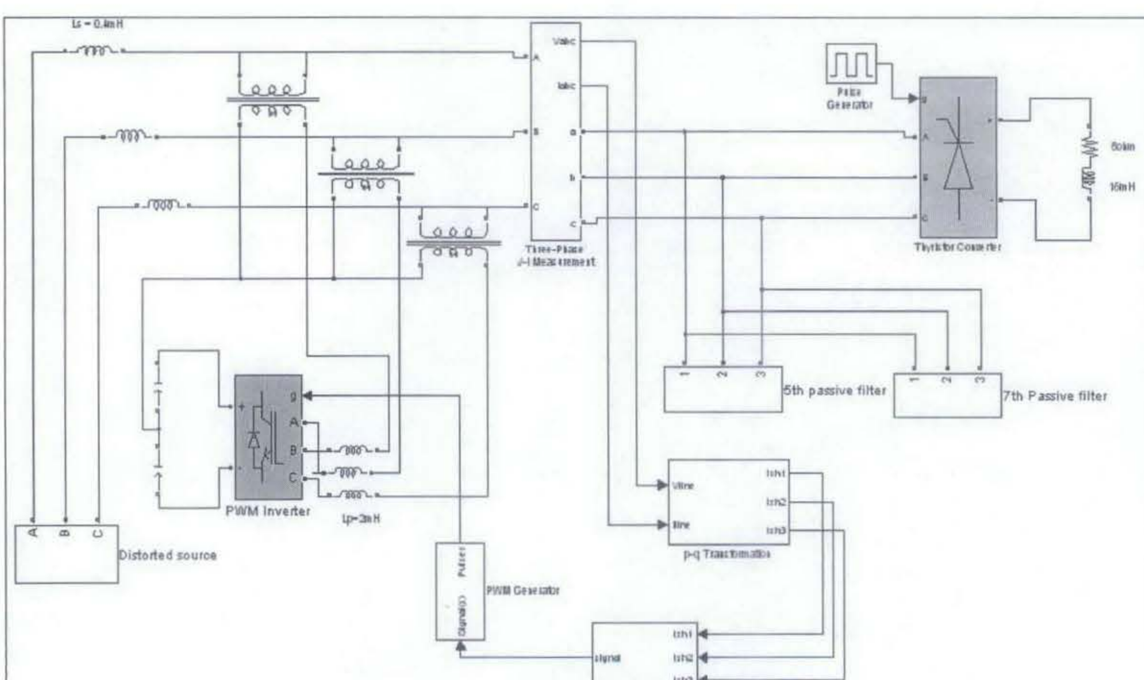


Figure 3.3: A thyristor converter circuit with combination of series active filter and shunt passive filter

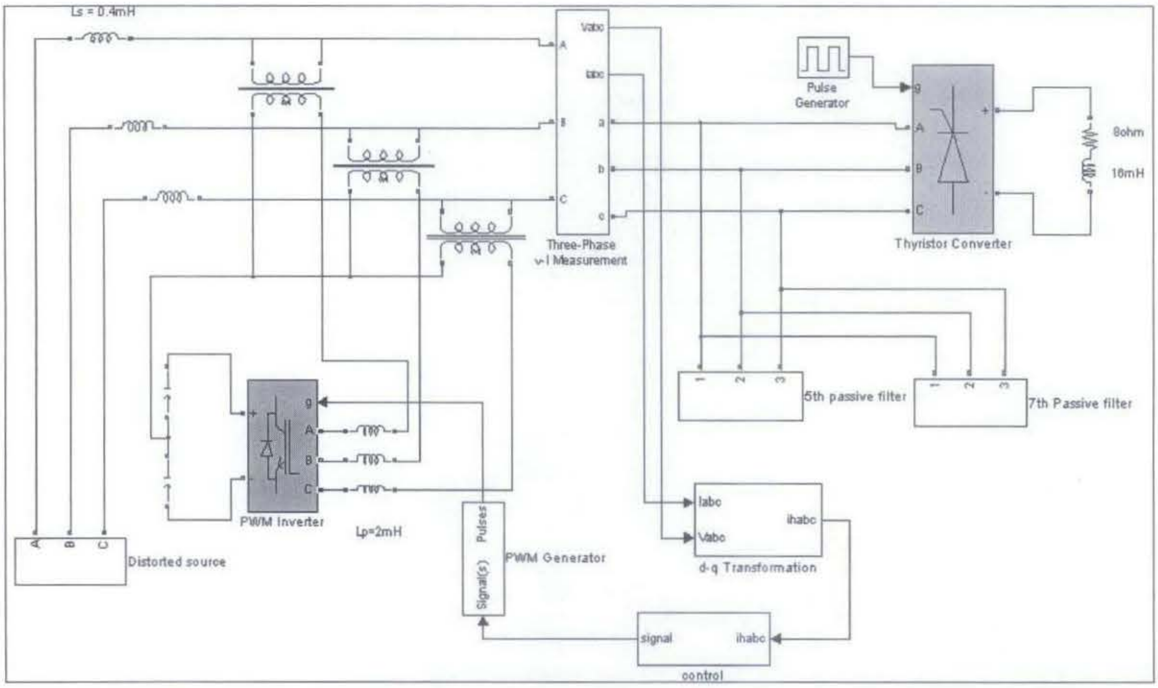


Figure 3.4: A thyristor converter circuit with combination of series active filter and shunt passive filter

3.2 DESCRIPTION OF THE MODELS

The description of the models will cover the important part of the model. This includes the shunt passive filter, the secondary ripple filter, the p-q control scheme and the i_d-i_q control scheme.

3.2.1 Shunt Passive Filter

The passive filter is connected in parallel to the circuit and it was designed to filter the fifth and seventh harmonic. Since the filter aim at compensating the voltage source harmonic produces by a six-pulse thyristor converter, it is known that the typical highest harmonic is the fifth and seventh harmonic. The filter designed is a single-tuned filter also called low-pass or bandpass filter which is most commonly applied. Figure 3.5 below shows an equivalent circuit for harmonic injection in the system. The first junction represents the passive filter with the harmonic current flowing through, I_F and the second junction represents the source impedance of the system with the current, I_s.

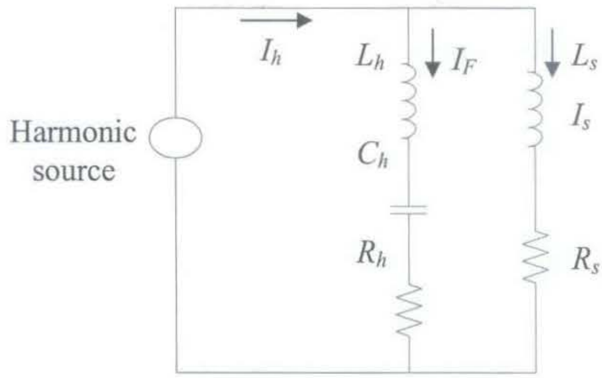


Figure 3.5: Equivalent circuit for harmonic injection in the system

I_h is the injected harmonic current which is produced by the load in the simulated model. The current in the filter, I_F is given by:

$$I_F = \frac{Z_S}{Z_S + Z_f} I_h = \rho_f I_h \ ,$$

and the current component flowing through the source, I_s is given by:

$$I_S = \frac{Z_f}{Z_S + Z_f} I_h = \rho_s I_h$$

The total impedance of the filter circuit is the total of resistance and reactance. The system impedance plays an important role in the filtration process. For infinite system impedance, the filtration will be perfect where all harmonics will flow through the filter impedance. Thus, a proper selection of the R, L and C must ensure that it provides high impedance in the system. In a single tuned filter, the inductive and capacitive reactance should be equal at the tuned frequency.

$$Z = R + 2\pi f_r L + \frac{1}{2\pi f_r C} = R$$

Simplification of this gives us;

$$2\pi f_r L = \frac{1}{2\pi f_r C},$$

Therefore, the resonant frequency of the filter is given by:

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

The quality, Q of the passive filter is defined as:

$$Q = \frac{2\pi f_r L}{R} = \frac{\omega_n L}{R}$$

To design the fifth harmonic filter with operating frequency of 50Hz, the tuned frequency is set to be 250Hz and capacitor value is first set to 34μF. The capacitor value is chosen based on the previous work done [2, 3]. From this based value, the optimum value of capacitor and inductor is work out by a trial and error basis.

Calculation:

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

$$250 = \frac{1}{2\pi\sqrt{34\mu \cdot C}}$$

$$C = \frac{4.053 \times 10^{-7}}{34\mu} = 11.92mH \approx 12mH$$

To design the seventh harmonic filter with operating frequency of 50Hz, the tuned frequency is set to be 350Hz and capacitor value is first set to 34μF. The capacitor is first taken to be the same.

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

$$350 = \frac{1}{2\pi\sqrt{34\mu \cdot C}}$$

$$C = \frac{2.068 \times 10^{-7}}{34\mu} = 6.08mH \approx 6mH$$

Several pairs of capacitor and inductor value for fifth and seventh filter is calculated and simulated in the model. The list is as shown in the table 3.1 below:

Table 3.1: Possible pairs of capacitor and inductor for shunt passive filter

	1		2		3	
	Fifth	Seventh	Fifth	Seventh	Fifth	Seventh
Inductor (mH)	12	6	12	12	6	6
Capacitor (μF)	34	34	34	68	68	136

3.2.3 The series active filter with p-q control method

The model of the filter is shown in figure 3.3. The series active filter is compose of a coupling transformer, a three phase PWM inverter with the control circuit that use the modulating current signal derived by a p-q method. The total apparent power of each transformer is 1/3 of the total apparent power of the inverter and the turn ratio is 20:1 with 400 turns in the secondary winding and 20 turns in the primary side. In general, the turn ratio must be high to reduce the amplitude of the inverter output current and to reduce the voltage induced across the primary winding [3].

PWM voltage source inverter

The inverter used is the normal sinusoidal PWM voltage source inverter. Three-phase VSI cover the medium to high-power applications. The main purpose of this topology is to provide a three-phase voltage source where the amplitude, phase and frequency of the voltages always be controllable. In this topology, the independently controlled ac output is a voltage waveform and it is most widely used because they naturally behave as voltage sources as required by many industrial applications. An inductive filter between the VSI ac side and the load is needed because the VSI generates an ac output voltage waveform composed of discrete values (high *dv/dt*). Thus, in order to produce a smooth current waveform the load side must be inductive at the harmonic frequencies. A capacitive load in the VSI will generate large current spikes. The inductive filter used in this model is 0.2mH which is a common and sufficient value to provide the inductive load to the VSI.

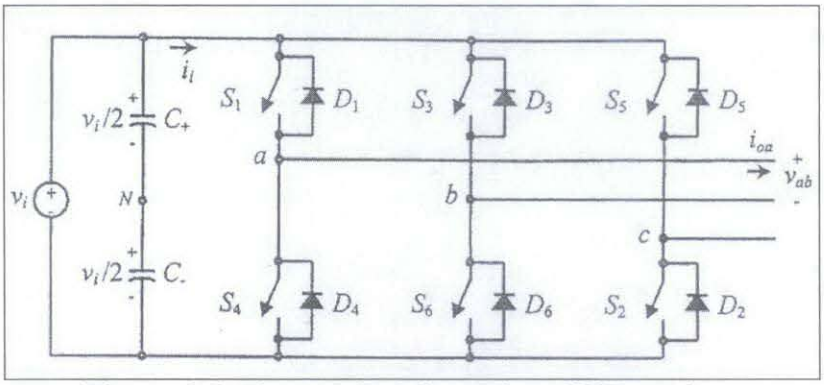


Figure 3.6: The standard three-phase VSI topology

Table 3.2: The valid switching states

State	State #	v_{ab}	v_{bc}	v_{ca}
S_1, S_2, and S_6 are on and S_4, S_5, and S_3 are off	1	v_i	0	$-v_i$
S_2, S_3, and S_1 are on and S_5, S_6, and S_4 are off	2	0	v_i	$-v_i$
S_3, S_4, and S_2 are on and S_6, S_1, and S_5 are off	3	$-v_i$	v_i	0
S_4, S_5, and S_3 are on and S_1, S_2, and S_6 are off	4	$-v_i$	0	v_i
S_5, S_6, and S_4 are on and S_2, S_3, and S_1 are off	5	0	$-v_i$	v_i
S_6, S_1, and S_5 are on and S_3, S_4, and S_2 are off	6	v_i	$-v_i$	0
S_1, S_3, and S_5 are on and S_4, S_6, and S_2 are off	7	0	0	0
S_4, S_6, and S_2 are on and S_1, S_3, and S_5 are off	8	0	0	0

Figure 3.6 shows the standard three-phase VSI topology which is used in this model. The two large capacitors are required to provide a neutral point N, such that the capacitor maintains a constant voltage $v_i/2$. A set of large capacitor is usually required since the current harmonics injected by the operation of the inverter are low order harmonics. For this model, the sufficient constant voltage needed is 400 V dc and thus the capacitor value chosen is 20 F each. The operation of the inverter is shown in the table 3.2 that gives the valid switching states. The switches of any leg of the inverter (S_1 and S_4, S_3 and S_6 or S_2 and S_5) cannot be switched on simultaneously because this will result in a short circuit across the dc link voltage supply. This switching is controlled by the pulses signal supplied to the PWM circuit.

The pulses are acquired when the sinusoidal control signal, $\hat{v}_c$ at desired frequency is compared with a triangular waveform, $\hat{v}_{tri}$ which used as a reference at specified frequency, f_s. The frequency of the triangular waveform establishes the inverter switching frequency and is generally kept constant along with its amplitude. The modulation index is given by the voltage magnitude of the triangular waveform divided by the control signal magnitude;

$$\text{Modulation index, } m_a = \frac{\hat{v}_c}{\hat{v}_{tri}}$$

The carrier frequency, f_s of the $\hat{v}_{tri}$ used in this model is 15 000 Hz and $\hat{v}_c$ is the peak amplitude of the control signal which is given by:

$$\hat{v}_c = K \cdot i_{sh}$$

Where K is the gain that is set to 4 and i_{sh} is the harmonic current derived from the control scheme using different control method. The modulation index is then depends on the control voltage amplitude and is always less than 1.0.

The desired ac output voltage from the inverter is the line voltage, i.e v_{ab} as shown in figure 3.5. This is the voltage needed to be supplied to the coupling transformer in order to inject high impedance to the circuit at harmonic frequency. The output voltage is given by:

$$v_{ab} = m_a * \sin \omega t * \frac{V_i}{2}$$

Thus the output voltage is dependent on the dc voltage where when $\hat{v}_c > V_{tri}$, $V_A = \frac{1}{2} V_d$ and for $\hat{v}_c < V_{tri}$, $V_A = -\frac{1}{2} V_d$.

Control Scheme

The derivation of the p-q method is similar to the step shown in the previous chapter. The aim of this control scheme is to get the reference voltage to be fed into the PWM VSI, where $\hat{v}_c = K \cdot i_{sh}$. Thus, it is required to generate the harmonic current sense from the line current in the system. In order to find the harmonic current, the p-q method is used to decompose the fundamental current and its harmonic component. The basic principle used in this method is to separate the fundamental and oscillatory component by filtering out the instantaneous active and reactive power. The instantaneous power is obtain from the derivation of line voltage and current in the system which contains the harmonic component. The reference current and voltage is taken from the source line current after the coupling transformer and is given as follows:

$$i_a = I_a \sin \omega t \qquad v_a = V_a \sin \omega t$$
$$i_b = I_b \sin(\omega t + 2\pi/3) \qquad v_b = V_b \sin(\omega t + 2\pi/3)$$
$$i_c = I_c \sin(\omega t - 2\pi/3) \qquad v_c = V_c \sin(\omega t - 2\pi/3)$$

The line voltage and current is decomposed into the static frame or also called $\alpha\beta$-frame. The decomposition is done by applying the matrix below:

$$\begin{bmatrix} v_{L\alpha} \\ v_{L\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

$$\begin{bmatrix} i_{S\alpha} \\ i_{S\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} i_{Sa} \\ i_{Sb} \\ i_{Sc} \end{bmatrix}$$

The $\alpha\beta$-frame is illustrated as in figure 3.7. Both voltages and currents are put into a new static frame with α and β-axis. From here, the instantaneous active and reactive power is then obtained by multiplying the line voltage and source current in $\alpha\beta$ frame as follows:

$$\begin{bmatrix} p_S \\ q_S \end{bmatrix} = \begin{bmatrix} v_{L\alpha} & v_{L\beta} \\ v_{L\beta} & -v_{L\alpha} \end{bmatrix} \cdot \begin{bmatrix} i_{S\alpha} \\ i_{S\beta} \end{bmatrix}$$

The harmonic components of p_s and q_s are then extracted by applying a filter which utilizing the Laplace transformation. The method proposed in[5] and [6] had used a high pass filter (HPF) to filter out the oscillatory component. However, in this model, a low-pass filter (LPF) is used to filter out the dc component and is subtracted from the instantaneous power to acquire the oscillatory component. Figure 3.7 shows the operation of the filter which is a Butterworth second order filter with cut-off frequency of 25Hz. The matrix of the filtering operation is given as follows:

$$\begin{bmatrix} P_{Sh} \\ Q_{Sh} \end{bmatrix} = H(s) \begin{bmatrix} P_S \\ Q_S \end{bmatrix}$$

where $H(s) = s/(s - \omega_c)$; ω_c is the LPF cut-off frequency

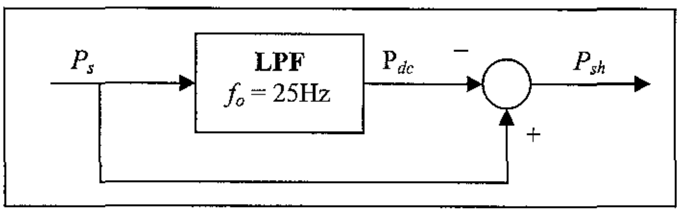


Figure 3.7: The filtering operation of power through LPF

Resulting p and q composed of the oscillatory or ac and average or dc component.

$$p_l = \tilde{p}_l + P_l \quad \text{and} \quad q_l = \tilde{q}_l + Q_l$$

From the harmonic component of the instantaneous power obtained, the current source harmonic in the $\alpha\beta$ frame is then calculated as follows:

$$\begin{bmatrix} i_{Sh\alpha} \\ i_{Sh\beta} \end{bmatrix} = \frac{1}{v_{L\alpha}^2 + v_{L\beta}^2} \begin{bmatrix} v_{L\alpha} & v_{L\beta} \\ v_{L\beta} & -v_{L\alpha} \end{bmatrix} \begin{bmatrix} p_{Sh} \\ q_{Sh} \end{bmatrix}$$

At this stage, the harmonic line current in $\alpha\beta$ frame is found and the current is then transform back into line current with the following transformation:

$$\begin{bmatrix} I_{Sha} \\ I_{Shb} \\ I_{Shc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{Sh\alpha} \\ i_{Sh\beta} \end{bmatrix}$$

The voltage series filter is calculated by multiplying it by gain, K:

$$\begin{bmatrix} v_{Ca} \\ v_{Cb} \\ v_{Cc} \end{bmatrix} = K \begin{bmatrix} i_{Sha} \\ i_{Shb} \\ i_{Shc} \end{bmatrix}$$

The gain K is a constant value that determines the impedance level applied across the coupling transformer and the value was determined by the trail and error. The smallest value of K possible is 4. The voltage obtained is the reference voltage that is fed into the PWM control circuit to generate the pulses of the inverter.

3.2.4 The series active filter with i_d-i_q control method

The general figure of the model is shown in figure 3.4. The construction of the model is similar with the previous model but different in the control scheme used to obtain the reference voltage to the PWM control circuit. In this section, only the control scheme which is the instantaneous active and reactive current component i_d-i_q method is discussed. Other components value i.e coupling transformer, passive filter, inductance and load remained the same.

Control Scheme of i_d-i_q method

The different of this method is that it uses directly the line current to obtain its harmonic component as oppose to the previous method that used instantaneous power. Thus, the current i_{Sh} are obtained from the instantaneous active and reactive component i_{ld} and i_{lq} of the nonlinear load. Instead of using a static $\alpha\beta$ frame, this method applied the dq0 transformation which is based on a synchronous rotational frame. In a simple explanation, the voltage or current is derived in the d-q axis that represents the x-y axis and is synchronously rotating at a constant speed, ω. Thus, the current or voltage component obtained will be a dc component at a fundamental frequency and is an ac component or oscillatory at other frequencies. This transformation is also called the park transformation. The Park transformation will eliminates time-varying inductances by referring the current or voltage quantities to a fixed or rotating reference frame. The line current to the load is taken and transform into d-q frame as follows:

$$I_d = \frac{2}{3}(I_a \sin(\omega t) + I_b \sin(\omega t - 2\pi/3) + I_c \sin(\omega t + 2\pi/3))$$

$$I_d = \frac{2}{3}(I_a \cos(\omega t) + I_b \cos(\omega t - 2\pi/3) + I_c \cos(\omega t + 2\pi/3))$$

$$I_o = \frac{1}{3}(I_a + I_b + I_c)$$

ω is the rotation speed in rad/sec of the rotating frame. In order to perform this transformation, the phase-locked loop (PLL) is utilized to generate the sine and cosine components. The fundamental frequency is set to 50Hz and the input line voltage is fed into the PLL block as a basis to generate the sine and cosine function needed. I_o is the zero component produced and the other two are composed of fundamental and oscillatory components. To put the transformation into matrix of d and q component, it is derived as below:

$$I_{dq} = \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \sin\omega t & \cos\omega t \\ -\cos\omega t & -\sin\omega t \end{bmatrix} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} i_{df} + i_{dh} \\ i_{qf} + i_{qh} \end{bmatrix}$$

i_{df} is the fundamental active component of d-axis direct current component and i_{dh} is the harmonic active component of d-axis alternate component. For q-axis, i_{qf} is the fundamental reactive component of q-axis direct current component and i_{qh} is the harmonic reactive component of q-axis alternate component. The harmonic current of d and q component is filtered out to be the reference current to the inverter. In order to perform this, the second order low-pass filter with cut-off frequency of 15 Hz is used. The transformation and filtering operation are shown in figure 3.8 below:

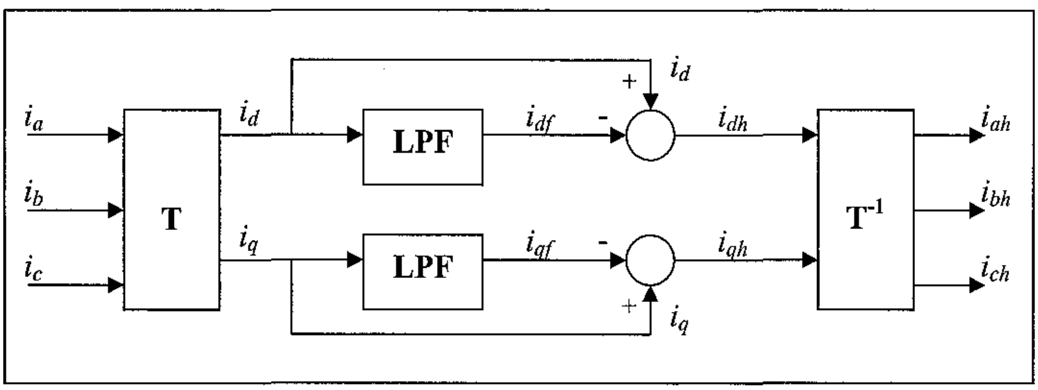


Figure 3.8: The transformation and filtering operation of power through LPF

The block **T** indicates the transformation of *abc* to *d-q* coordinate and $\mathbf{T}^{-1}$ is the transformation from *d-q* to *abc* coordinate. When the current, i_d and i_q is put through the low-pass filter (LPF), the first harmonic current of positive sequence is transform to dc quantities and all higher order current harmonics including first harmonic current of negative sequence are transformed to ac quantities. Thus, the output from the filter is the dc component which contains the current at fundamental frequency. In order to get the harmonic current component, the output current from the filter is subtracted from the current, i_d and i_q which produced the harmonic current component, i_{dh} and i_{qh}. These currents are then transformed back into line current in *abc* coordinate. This transformation is performed by the following equation:

$$I_{ah} = I_{dh}\sin(\omega t) + I_{qh}\cos\omega t + I_o$$
$$I_{bh} = I_{dh}\sin(\omega t - 2\pi/3) + I_{qh}\cos(\omega t - 2\pi/3) + I_o$$
$$I_{ch} = I_{dh}\sin(\omega t - 2\pi/3) + I_{qh}\cos(\omega t + 2\pi/3) + I_o$$

These harmonic currents are then multiplied by a constant gain of 6. The gain, K is found by the trial and error method as in the previous method. The voltage series filter is calculated by multiplying it by gain, *K*:

$$\begin{bmatrix} v_{Ca} \\ v_{Cb} \\ v_{Cc} \end{bmatrix} = K \begin{bmatrix} i_{ha} \\ i_{hb} \\ i_{hc} \end{bmatrix}$$

CHAPTER 4
RESULT AND DISCUSSION

4.1 RESULT

Result obtained in this project is divided into two parts. The first one is the comparison of the %THD measurement between the system without using any filter and when the filter is in operation either only shunt passive filter or series active filter or both is applied to the system. There are two condition of the source inductance used which are 0.4mH and 0.6mH for all cases in order to analyze the performance of the filter at different percentage of inductance present in the system. The second part is the result obtained for different control method used for the combination of the series filter and shunt passive filter; the p-q and id-iq method. The source inductance used here is 0.4mH and the performance is analyzed for different supply source condition which are the balanced sinusoidal, the unbalanced sinusoidal and the balanced non-sinusoidal supply condition. The analysis of the result is done in the discussion section.

4.1.1 Part I

The result for the system without any filter in operation, the system with only shunt passive filter is in operation, system with only series active filter in operation and the system with combination of both filters in operation is shown below. The waveform of the input source current, I_{in} output current, I_{out} and current in shunt passive filter and the %THD measurement of the output current is givens in the following figures. There two cases of different source inductance value present in the network tested for each model; where L_s = 0.4mH and L_s = 0.6mH.

The system without shunt passive filter and series active filter

The result is shown in figure 4.1, 4.2, 4.3 and 4.4 below.

1. Source inductance, L_s = 0.4mH

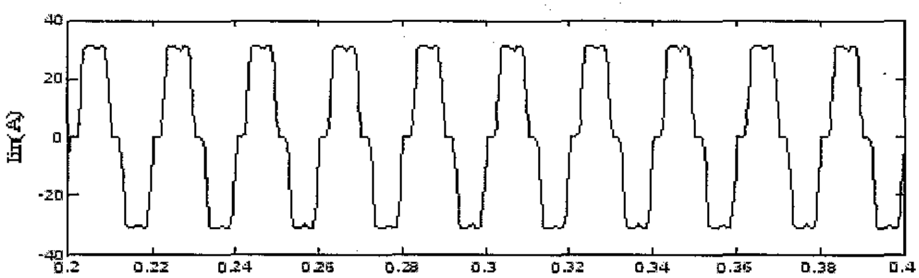


Figure 4.1: The input current, I_{in} waveform for the system without any filter with L_s = 0.4mH

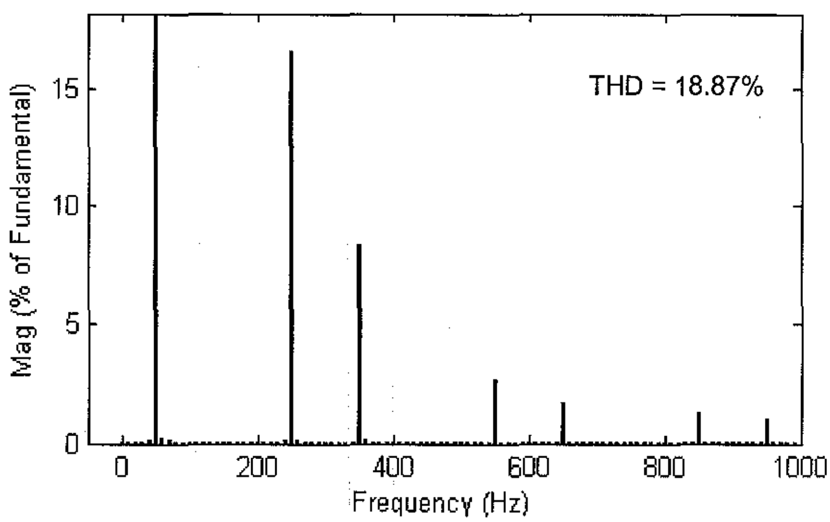


Figure 4.2: %THD of the input current waveform for the system without any filter with L_s = 0.4mH

2. Source inductance, L_s = 0.6mH

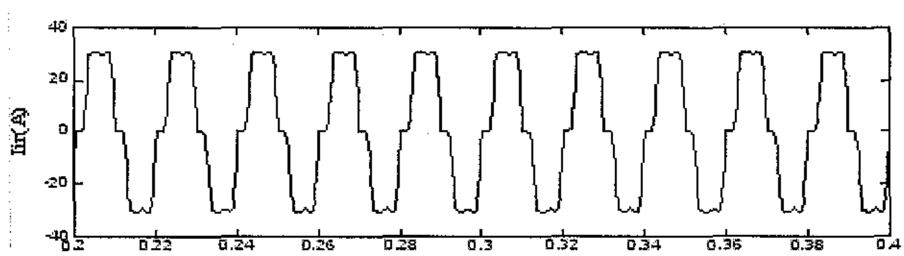


Figure 4.3: The input current, I_{in} waveform for the system without any filter with L_s = 0.6mH

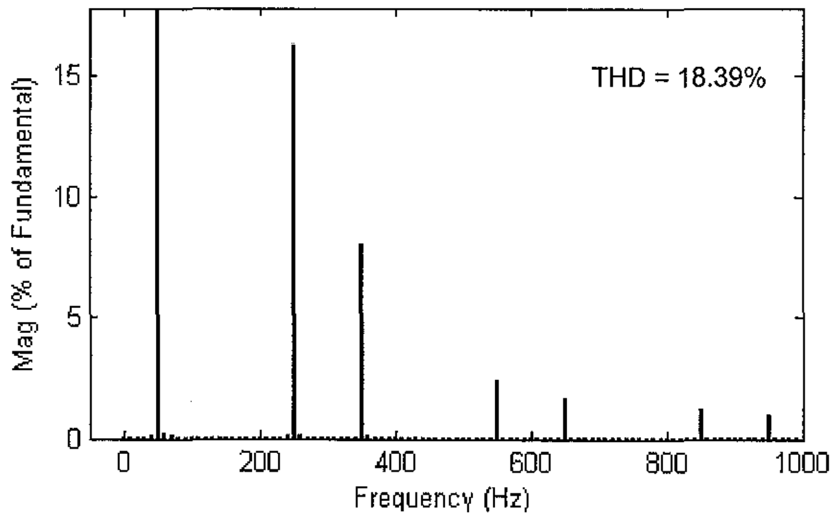


Figure 4.4: %THD of the input current waveform for the system without any filter with Ls = 0.6mH

The system with shunt passive filter only

The simulated model is shown in the figure 3.1 and the result as in figure 4.5, 4.6, 4.7 and 4.8 below.

1. Source inductance, L_s = 0.4mH

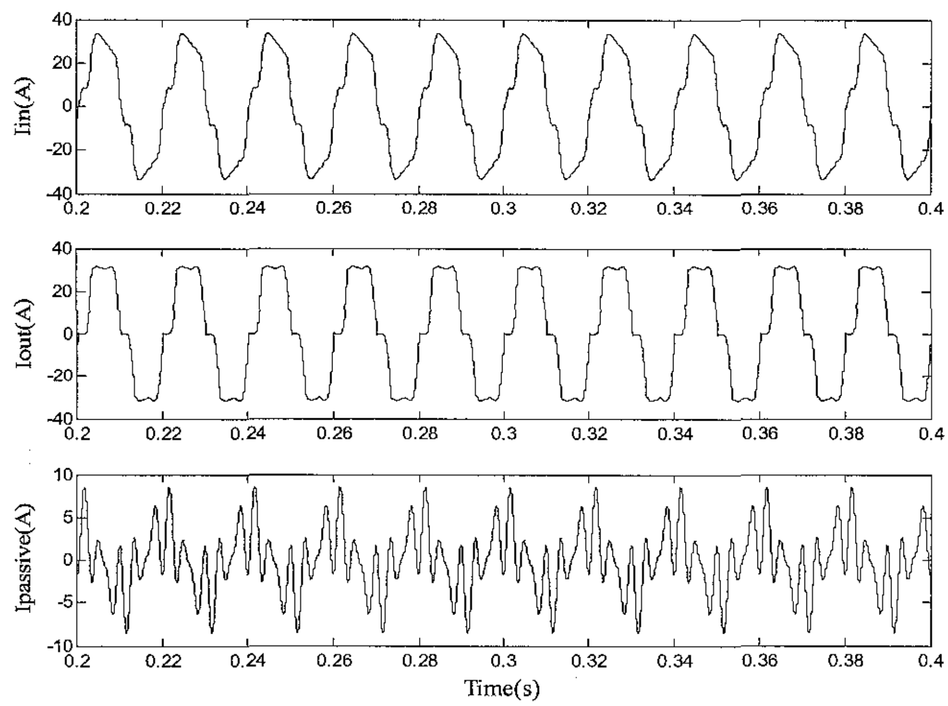


Figure 4.5: The input current, I_{in} and output current, I_{out} waveform for the system with shunt passive filter only and L_s = 0.4mH

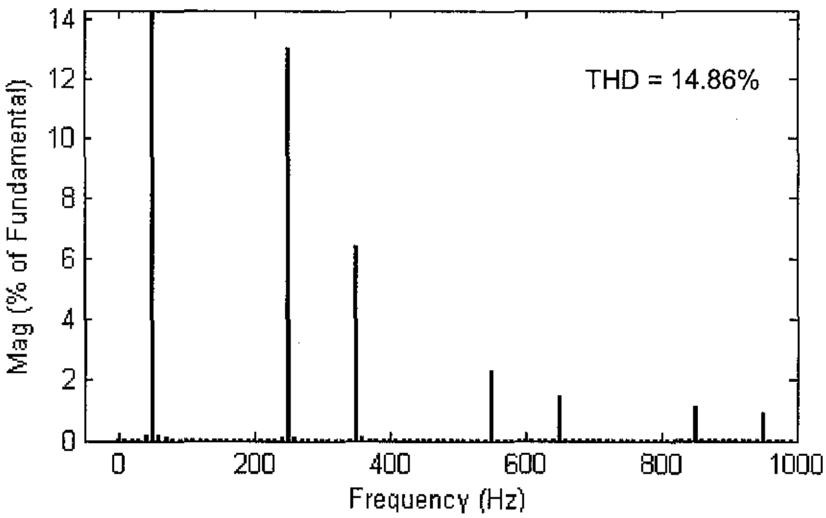


Figure 4.6: %THD of the input current for the system with shunt passive filter only and Ls = 0.4mH

2. Source inductance, L_s = 0.6mH

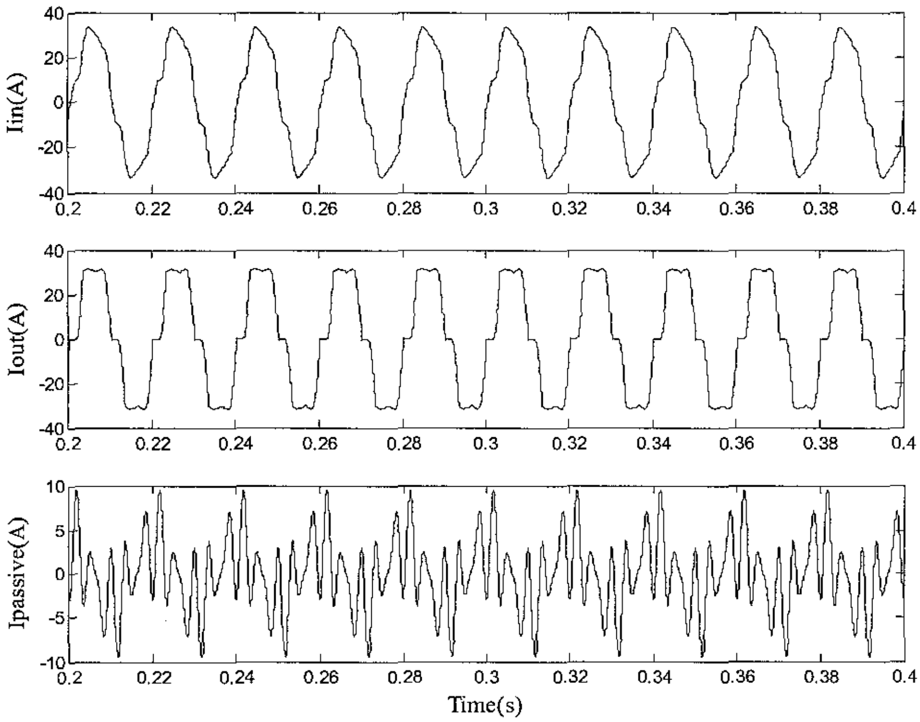


Figure 4.7: The input current, I_{in} and output current, I_{out} waveform for the system with shunt passive filter only and L_s = 0.6mH

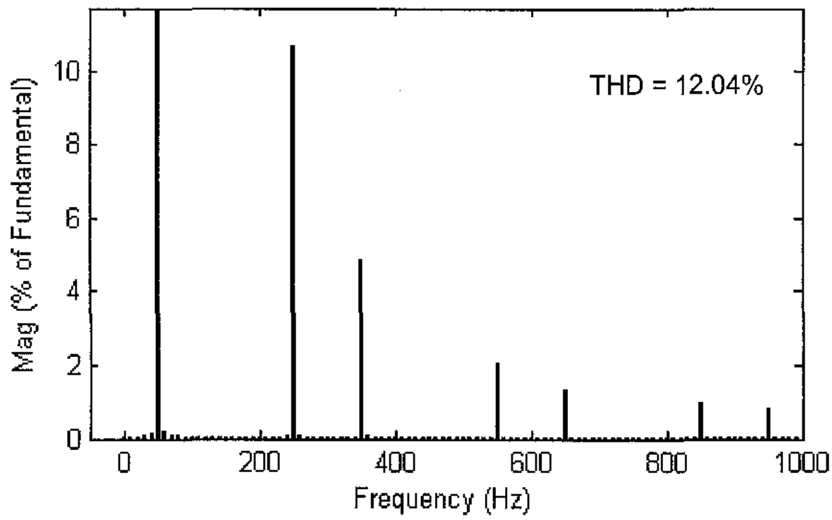


Figure 4.8: %THD of the input current for the system with shunt passive filter only and L_s = 0.6mH

The system with series active filter only

The simulated model of the system with series active filter in operation is shown in the figure 3.2 and the result is shown in figure 4.9, 4.10, 4.11 and 4.12 below.

1. Source inductance, L_s = 0.4mH

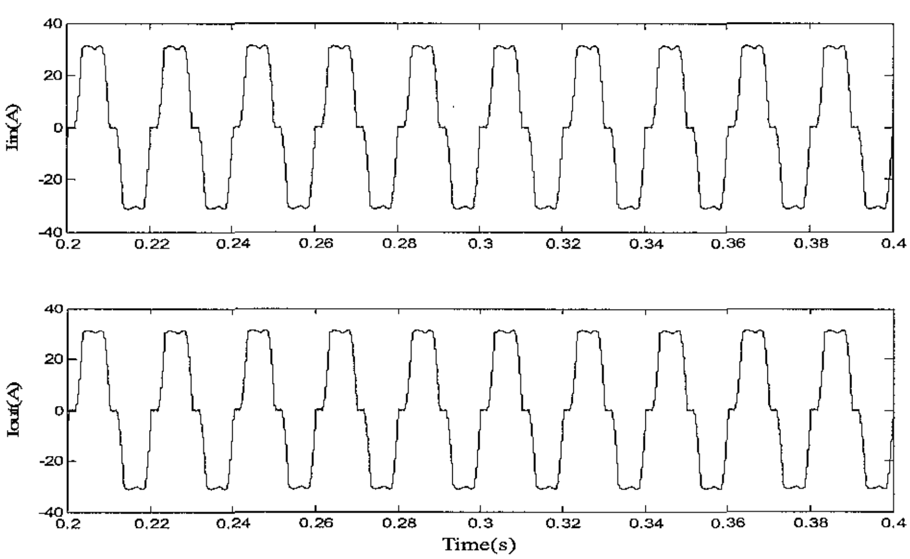


Figure 4.9: The input current, I_{in} and output current, I_{out} waveform for the system with series active filter only and L_s = 0.4mH

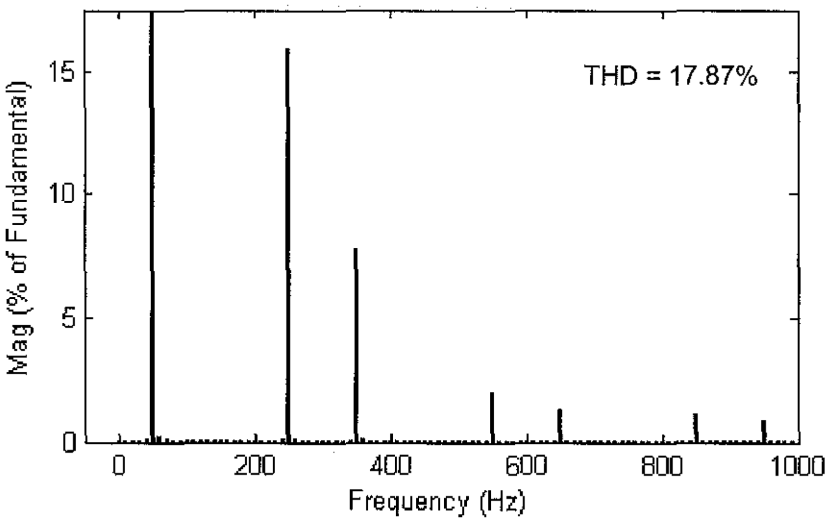


Figure 4.10: %THD of the input current for the system with series active filter only and Ls = 0.4mH

2. Source inductance, $L_s = 0.6mH$

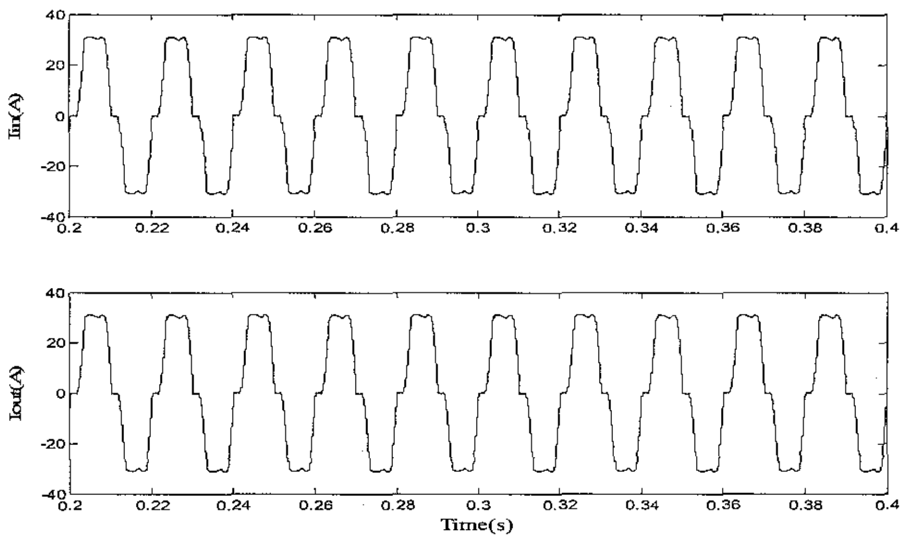


Figure 4.11: The input current, I_{in} and output current, I_{out} waveform for the system with series active filter only and $L_s = 0.6mH$

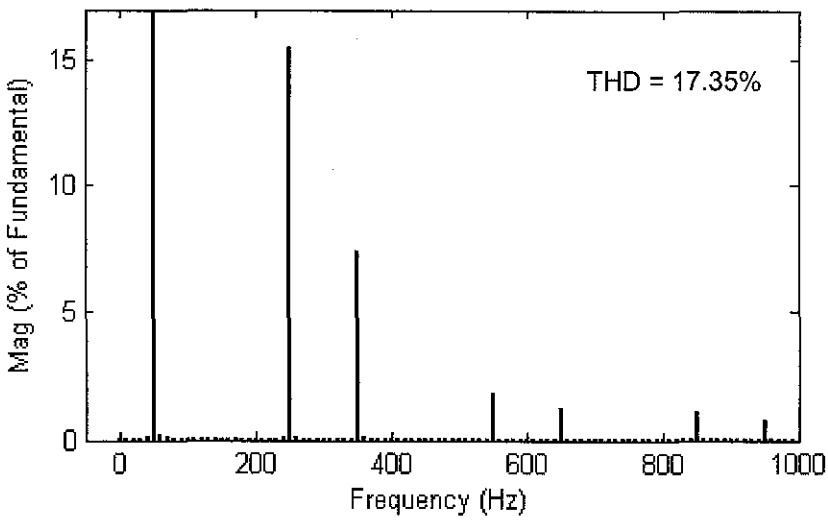


Figure 4.12: %THD of the input current for the system with series active filter only and Ls = 0.6mH

The system with combination of series active filter and shunt passive filter

The simulated model of the system with series active filter in operation is shown in the figure 3.3 and the result is shown in figure 4.13, 4.14, 4.15 and 4.16 below.

1. Source inductance, L_s = 0.4mH

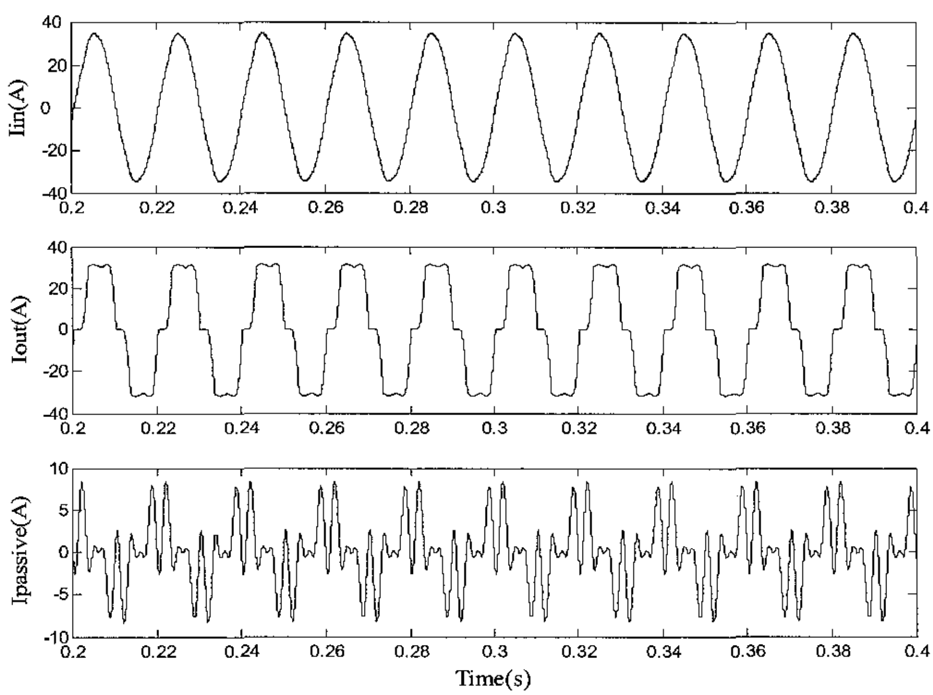


Figure 4.13: The input current, I_{in} and output current, I_{out} waveform for the system with combination of series active filter and shunt passive filter Ls = 0.4mH

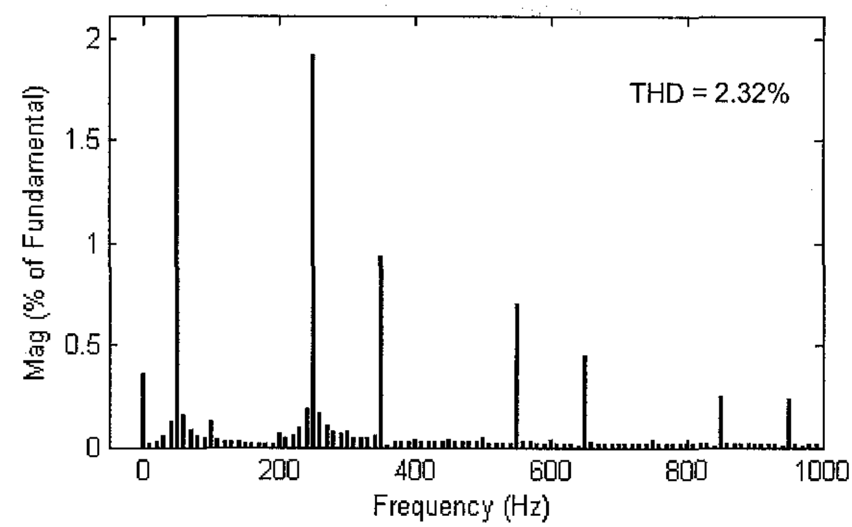


Figure 4.14: %THD of the input current for the system with combination of series active filter and shunt passive filter Ls = 0.4mH

2. Source inductance, L_s = 0.6mH

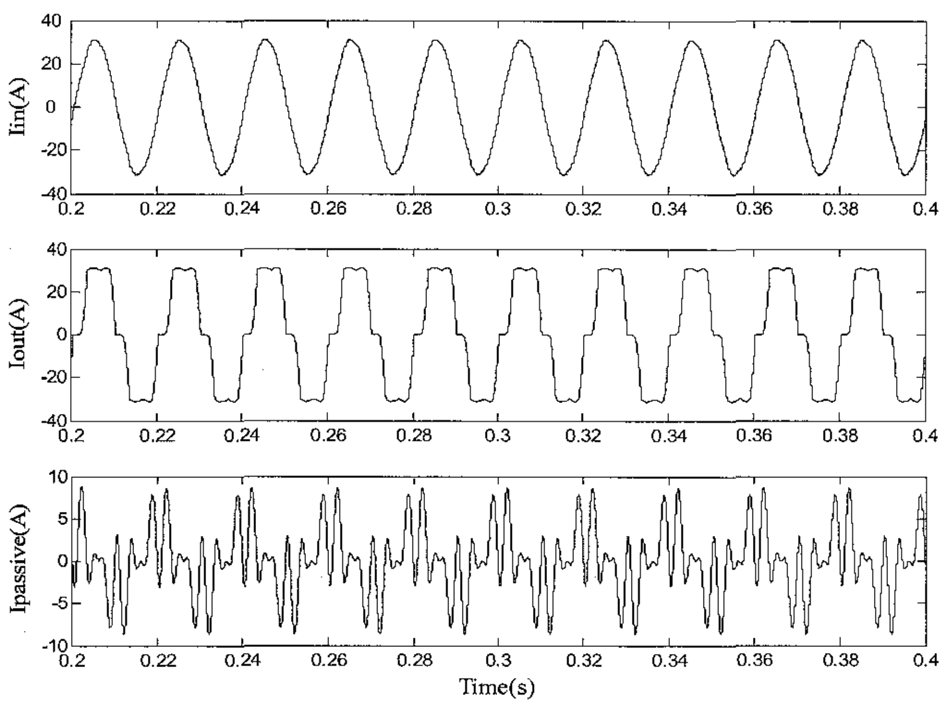


Figure 4.15: The input current, I_{in} and output current, I_{out} waveform for the system with combination of series active filter and shunt passive filter Ls = 0.6mH

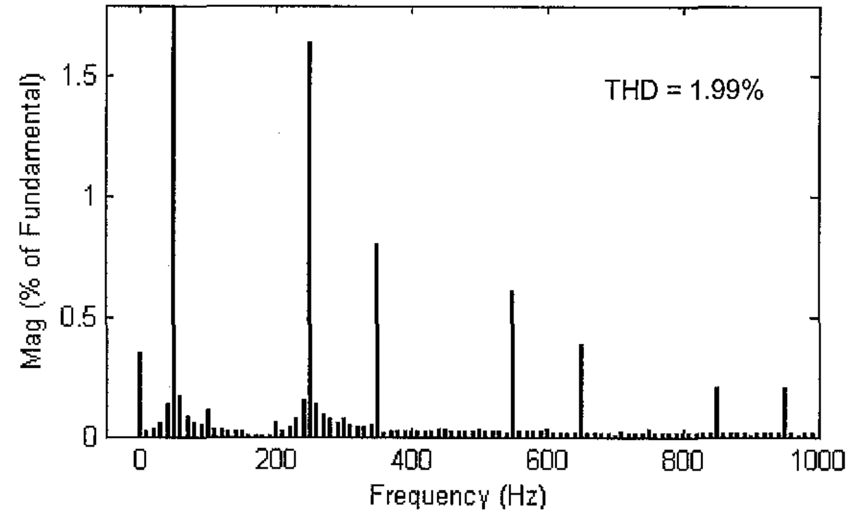


Figure 4.16: %THD of the input current for the system with combination of series active filter and shunt passive filter Ls = 0.6mH

4.1.2 PART II

The result for the system with the combination of series active and shunt passive filter in operation which using instantaneous active and reactive power method (p-q method) and instantaneous active and reactive current components (i_d-i_q method) is shown below. The waveform of the input source current, I_{in} output current, I_{out} and current in shunt passive filter and the %THD measurement of the output current is givens in the following figures. There are three cases of different supply source condition that is the balanced sinusoidal supply, unbalanced sinusoidal supply and balanced non-sinusoidal supply.

Case I: Balanced sinusoidal supply

Figure 4.17 and 4.18 shows the result for the series active filter used the p-q method and figure 4.19 and 4.20 shows the result when series active filter used the i_d-i_q method.

1. Instantaneous active and reactive power method (p-q method)

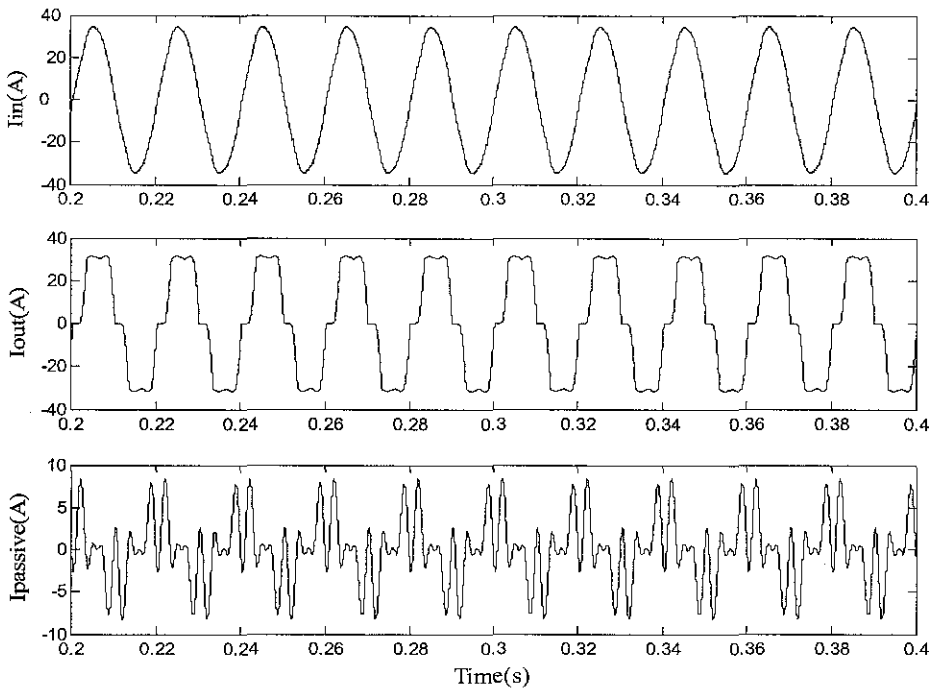


Figure 4.17: The input current, I_{in} and output current, I_{out} and current through passive filter, $I_{passive}$ waveform for the combined system using p-q method

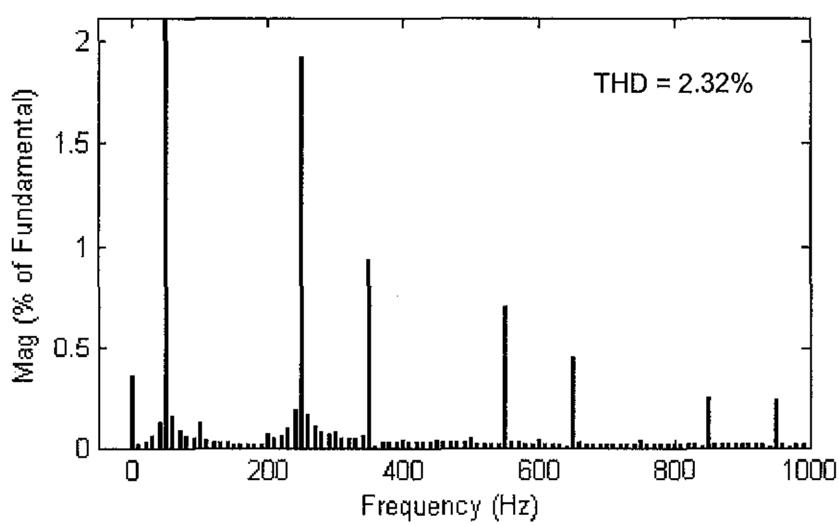


Figure 4.18: %THD of the input current for the combined system using p-q method

2. Instantaneous active and reactive current components (i_d-i_q method)

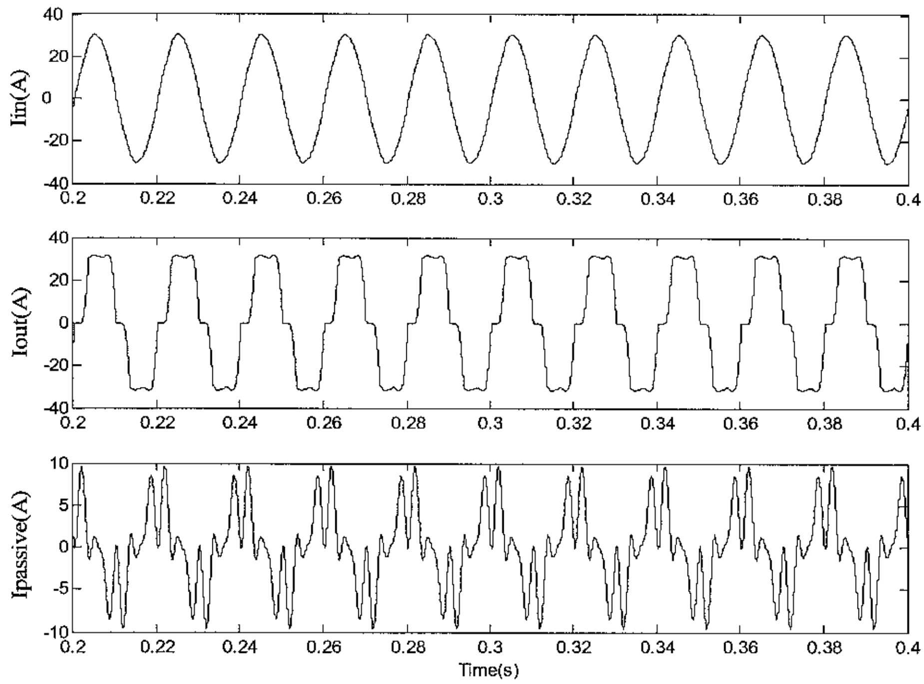


Figure 4.19: The input current, I_{in} and output current, I_{out} and current through passive filter, $I_{passive}$ waveform for the combined system using i_d-i_q method

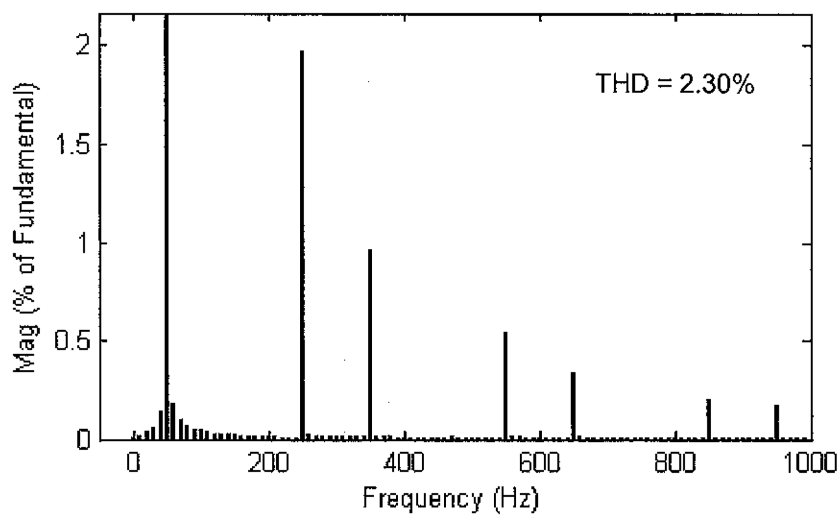


Figure 4.20: %THD of the input current for the combined system using i_d-i_q method

Case II: Balanced non-sinusoidal supply

Figure 4.21 and 4.22 shows the result for the series active filter used the p-q method and figure 4.23 and 4.24 shows the result when series active filter used the i_d-i_q method.

1. Instantaneous active and reactive power method (p-q method)

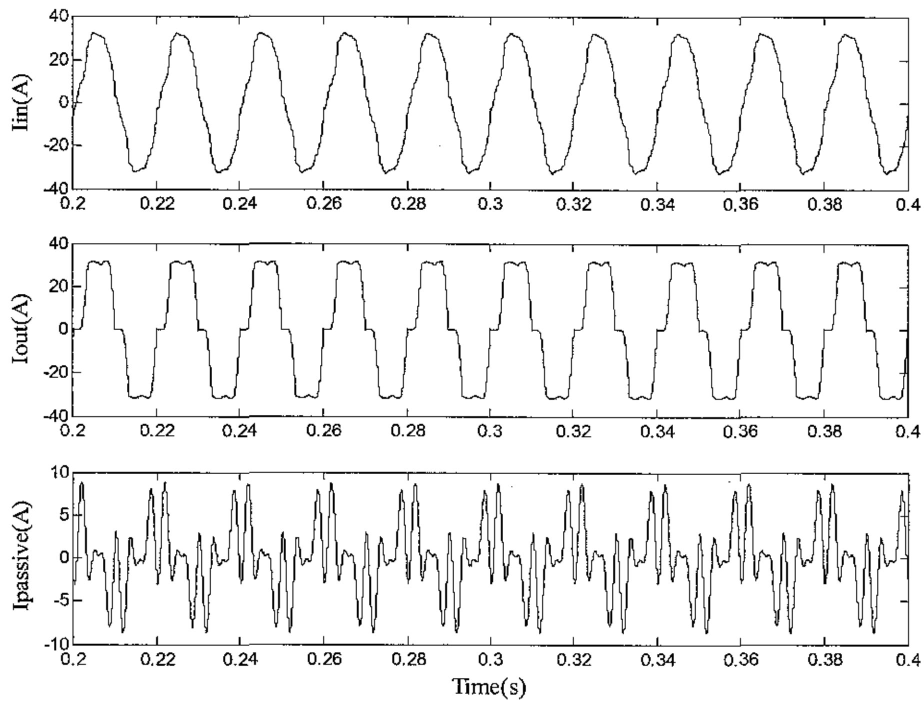


Figure 4.21: The input current, I_{in} and output current, I_{out} and current through passive filter, $I_{passive}$ waveform for the combined system using p-q method

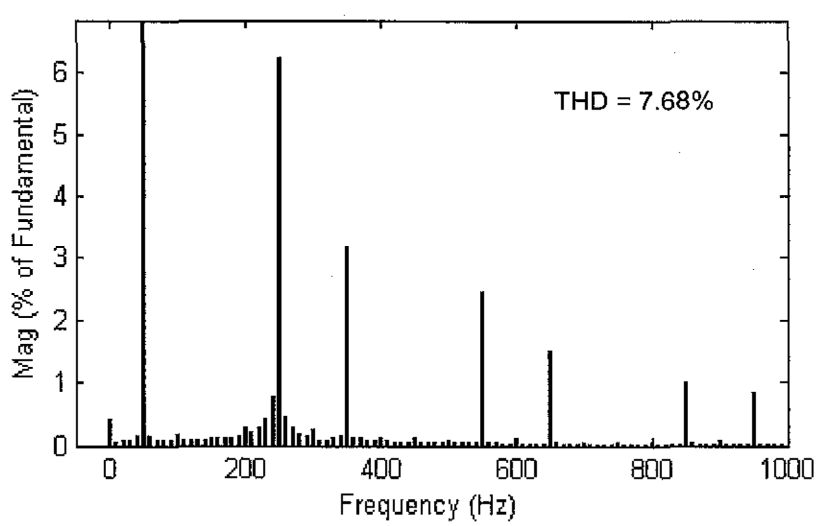


Figure 4.22: %THD of the input current for the combined system using p-q method

2. Instantaneous active and reactive current components (i_d-i_q method)

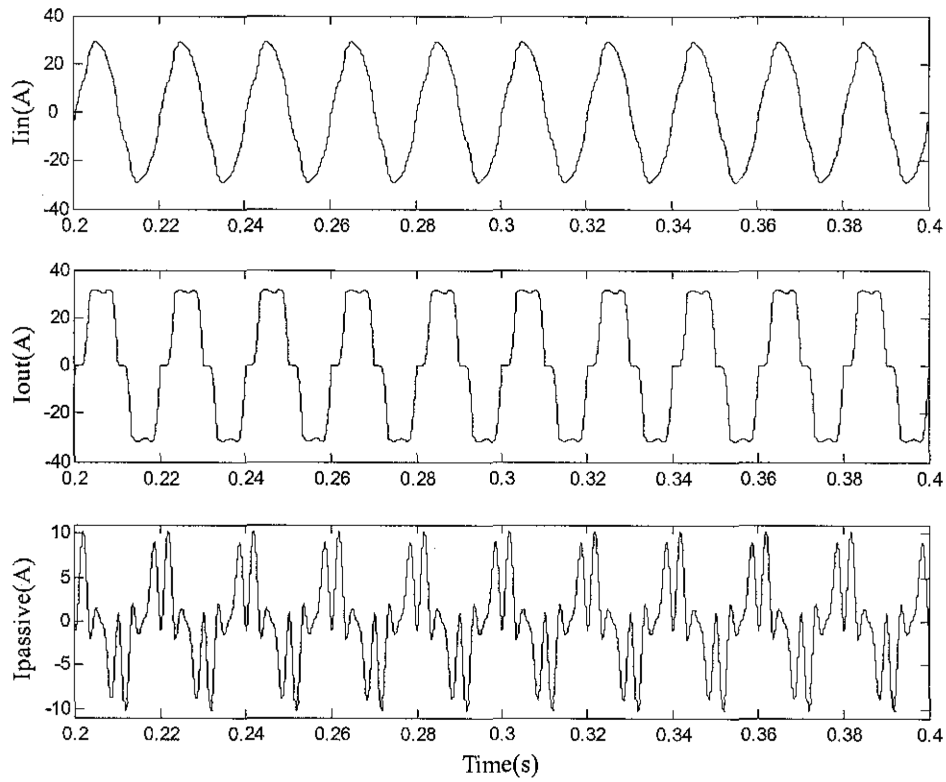


Figure 4.23: The input current, I_{in} and output current, I_{out} and current through passive filter, $I_{passive}$ waveform for the combined system using i_d-i_q method

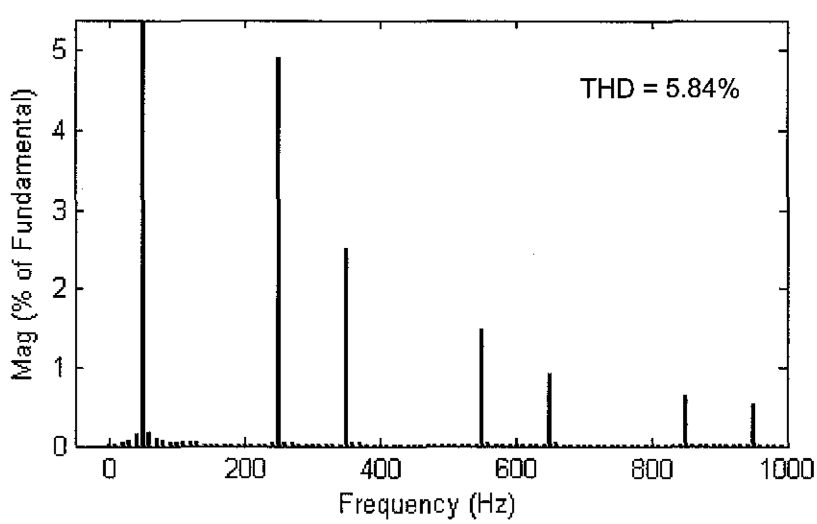


Figure 4.24: %THD of the input current for the combined system using i_d-i_q method

Case II: Unbalanced sinusoidal supply

Figure 4.25 and 4.26 shows the result for the series active filter used the p-q method and figure 4.27 and 4.28 shows the result when series active filter used the i_d-i_q method.

1. Instantaneous active and reactive power method (p-q method)

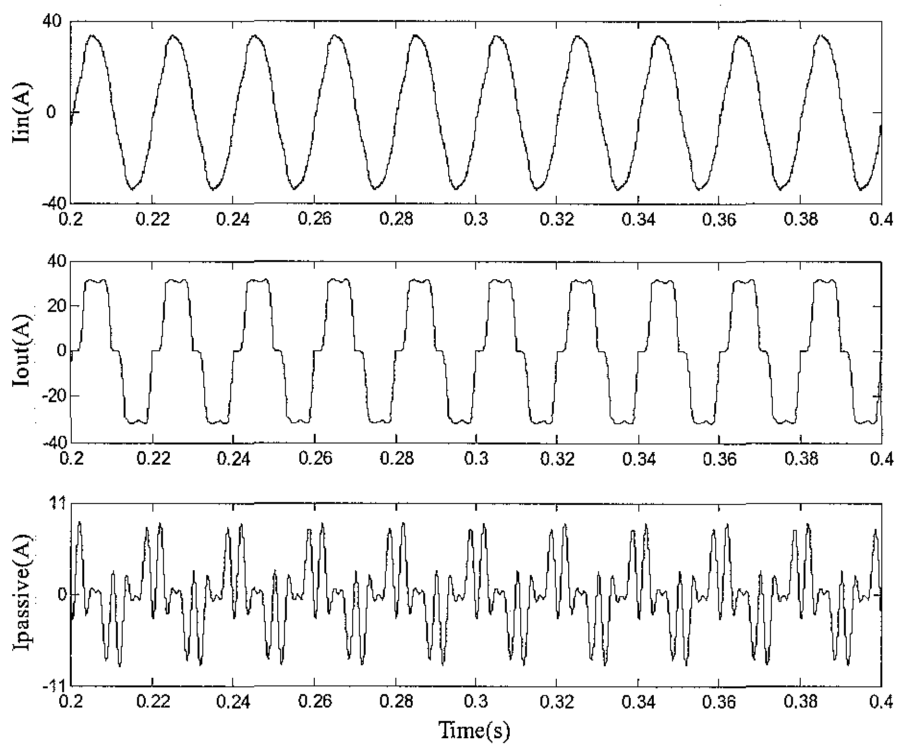


Figure 4.25: The input current, I_{in} and output current, I_{out} and current through passive filter, $I_{passive}$ waveform for the combined system using p-q method

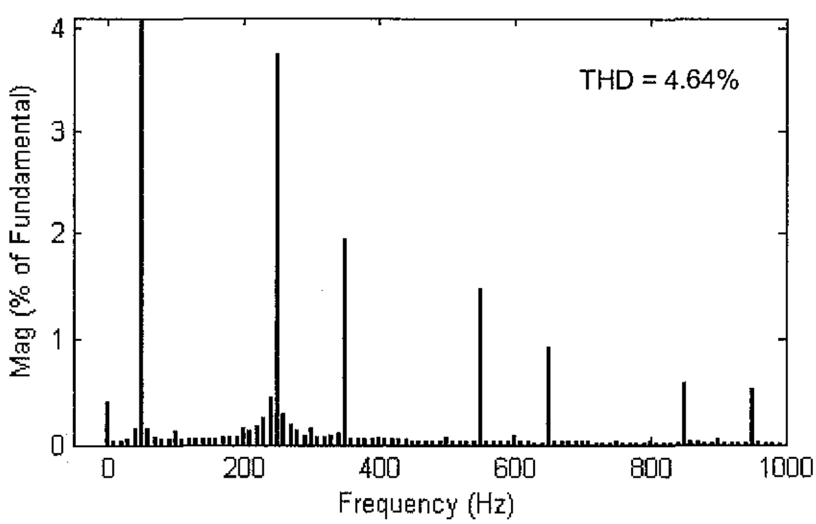


Figure 4.26: %THD of the input current for the combined system using p-q method

2. Instantaneous active and reactive current components (i_d-i_q method)

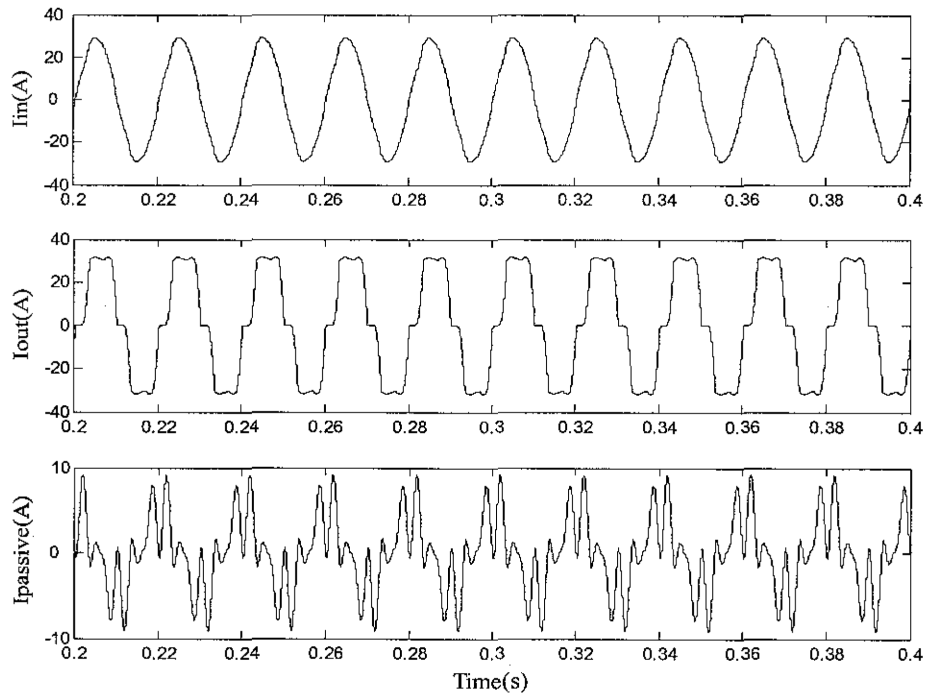


Figure 4.27: The input current, I_{in} and output current, I_{out} and current through passive filter, $I_{passive}$ waveform for the combined system using i_d-i_q method

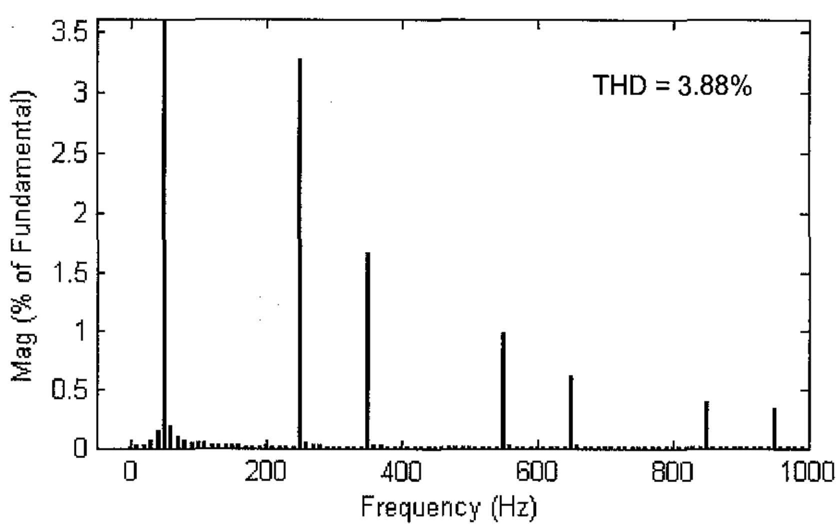


Figure 4.28: %THD of the input current for the combined system using i_d-i_q method

4.2 DISCUSSION

In this section, there is several part of the project that will be discussed in depth. It will cover the measurement of the performance used which is total harmonic distortion, the result obtained in part I and part II, the shunt passive filter and the comparison study of two different control methods used in this project.

4.2.1 Total Harmonic Distortion (THD)

The amount of distortion in the line current waveform is quantified by means of an index called the total harmonic distortion (THD). The THD is defined as the root mean square (RMS) value of the total harmonics of the signal, divided by the RMS value of its fundamental signal. The THD of current measured in this simulation is defined as:

$$\text{Total harmonic distortion, THD} = \frac{I_H}{I_F}\ ;$$

where I_F is the RMS value of fundamental current component;
and I_H is the harmonic current given by:

$I_H = \sqrt{I_2^2 + I_3^2 + \ldots\ldots + I_n^2}$ where I_n is the RMS value of the harmonic n

So, the percentage of THD is calculated as:

$$\%THD = 100 \times \frac{I_H}{I_F}$$

$$\%THD = 100 \times \sqrt{\sum_{n \neq 1} \left(\frac{I_n}{I_1}\right)^2}$$

The %THD is given directly from the model simulated in the Simulink. It also provides the indication of the level of each harmonic component in term of the magnitude of the fundamental component. The %THD indicates the harmonic content of the current measured where the higher the percentage means the higher the content of the harmonic in the current and vice versa. In other words, the more distorted the current waveform is, it will have higher %THD value.

4.2.2 Result of Part I - Effect of the filter in compensating the harmonic

The result obtained in part I shows the effect of the filter in compensating the harmonic. The comparison in the current waveform and its %THD measurement gives a clear indication of the role played by each of the filter in compensating the harmonic. The bar chart in figure 4.29 shows the comparison of the %THD value for four different cases; the system without any filter, system with shunt passive filter only, system with series active filter only and the combination of both filter in operation. Bar with a strip indicates the %THD for the system with source inductance of 0.4mH and the other is for source inductance of 0.6mH. From the bar chart, it can be concluded that the series active filter have a small effect in compensating the harmonic current while the shunt passive filter had a more significant role to compensate the harmonic current. However, the combination of both filters had enhanced significantly the ability of the filter to compensate the harmonic current. The detail of each system and their harmonic compensation will be discussed below.

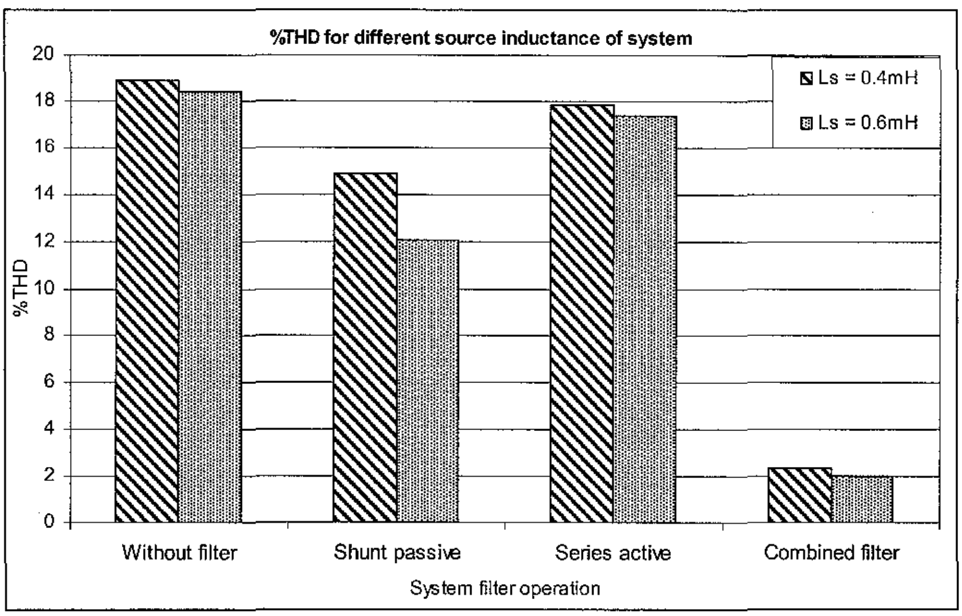


Figure 4.29: %THD of the input current for different source inductance of each case

i. The system without any filter

This model is simulated on purpose of to be the reference model. The content of the harmonic in the input line current without any filtering action is measured and current measurement of other filter is compared against this reference value in order to evaluate the performance of each filter. As shown in the bar chart in figure 4.29, the %THD for this system when L_s = 0.4mH is 18.87% and 18.39% when L_s = 0.6mH. This is the original value of harmonic present in the system.

After the filter is put into operation, this value is reduced which means a lower level of harmonic present in the input line current.

ii. System with shunt passive filter only

When the shunt passive filter is put into operation, the %THD of the line current is reduced, from 18.87% to 14.86% for L_s = 0.4mH and from 18.39% to 12.04% L_s = 0.6mH. The reduction of the %THD denotes that the shunt passive filter had compensated a small amount of harmonic in the line current. The filter was designed to sink the fifth and seventh harmonic across the system, and the compensated current, $I_{passive}$ is shown in figure 4.5 and 4.7. However, filtering characteristic of shunt passive filter partially depend on the source impedance which is not accurately known and is predominantly inductive. This caused the shunt passive filter to be less effective in compensating the harmonic. Low impedance in the system or network result in a lower compensation of harmonic and a higher impedance will gives a better harmonic compensation. This dependency of the harmonic compensation of the filter is undesirable since the impedance of the system might be changing and can be of low impedance. This downside of the filter and a less effective compensation gives an inspiration to improve the compensation characteristic of shunt passive filter. Besides from this, shunt passive filter might also cause the harmonic amplifying phenomenon where parallel resonance between source impedance and shunt passive filter occur.

iii. System with series active filter only

When the series active filter is put into operation, the %THD of the line current is reduced, from 18.78% to 17.87% for L_s = 0.4mH and from 18.38% to 17.35% for L_s = 0.6mH. This shows that the harmonic compensation of the input line current by the filter is less than the compensation of the shunt passive filter. As stated in the literature review, the series active filter is not very effective to compensate for the harmonic current but able to compensate the harmonic content in the voltage waveform. Since this model aim to compensate the harmonic current, it is obvious that the effect of the filter is not trivial in the current and voltage waveform as well. The series active filter work to compensate the harmonic by presenting high impedance across the system to the harmonic current component through the PWM inverter connected to the coupling transformer which is in series with the system. High impedance in the network will block the harmonic component from the load to the ac source and from ac source to the load side. However, this filter is unable to filter out the harmonic component in the line current since it cannot sink the harmonic content in the system. Since the series active filter can imposed high impedance to the system and blocked the load current harmonic to flow to the ac source side, it is an advantage to combine it with the shunt passive filter to improve the performance of both filters.

iv. System with the combination filter

When the combined filter of series active filter and shunt passive filter is put into operation, the %THD of the line current is significantly reduced, from 18.78% to 2.03% for L_s = 0.4mH and from 18.38% to 1.99% for L_s = 0.6mH. The result shows that the compensation of harmonic current is enhanced tremendously for the combined filter as compared to both filters acting alone. The series active filter in this combination used the p-q control method. As discussed previously, the shunt passive filter has a characteristic where the higher the source impedance, the better the filtering characteristic will be. However, the source impedance at fundamental frequency should have a negligible amount so that it does not cause any appreciable fundamental voltage drop. This requirement of the passive filter is provided by the active filter which is in series to the system. Since the active filter inserted high impedance across the system at harmonic frequency and zero impedance at fundamental frequency, it had certainly improved the performance of passive filter in compensating the harmonic. The compensation of these filers is described in the literature review part. Basically, the circuit can be represented by the equivalent circuit shown in figure 2.8, 2.9 and 2.10. The harmonic current flowing through the source is given as:

$$i_{sh} = \frac{Z_f}{Z_s + Z_f + K} \cdot i_{lh} + \frac{V_{sh}}{Z_s + Z_f + K}$$

In order to impose the resistance through the active filter, this harmonic current is multiplied by a gain *K* which is controlled by the voltage source inverter. The output voltage of the series active filter is given as:

$$v_c = K \cdot i_{sh} = K \cdot \frac{Z_f i_{lh} + V_{sh}}{Z_s + Z_f + K}$$

Where Z_f is the impedance of shunt passive filter, Z_s is the source impedance and K is the gain or the resistance implied to the circuit. From both of the equations above, it is noted that when K is much larger than Z_f and Z_s, i_{sh} is approximately zero and v_c is approximately given by $Z_f i_{lh} + V_{sh}$. Thus, the gain K should be designed such that it is much larger from the source and passive filter impedance in order to enhance the compensation. The gain chosen in this project is 4 which is the lowest possible value to give a satisfactory result. By applying a high gain of K, it also ensures that the source harmonic voltage does not appear on the load side since it as been applied across the series active filter as shown by this equation:

$$v_{fh} = -\frac{Z_s + K}{Z_s + Z_f + K} \cdot Z_f i_l + \frac{Z_f}{Z_s + Z_f + K} \cdot v_{sh}$$

From the result and the description of the compensation, it can be seen that the series active filter only operates as the harmonic isolator between the source and the load by imposing high impedance at harmonic frequencies. It also can eliminate the parallel resonance between shunt passive filter and source impedance and at the same time prevent the harmonic current produced by source from flowing into the passive filter. The harmonic component is then force to flow through the shunt passive filter and thus result in a good compensation of the harmonic current.

4.2.3 Result of Part II - Combination of series active and shunt passive filter

The result obtained in part II shows the role of combination of series active and passive filter of the filter in compensating the harmonics using two different control methods in three different condition of supply source. The aim of the result is to compare the effectiveness of both control methods in compensating the harmonic current when the supply is balanced sinusoidal, unbalanced sinusoidal and balanced non-sinusoidal. In order to make the comparison, the %THD of the input line current is measured for each case. Figure 4.30 shows the comparison of the %THD value for i_d-i_q method and p-q method for those three conditions of supply. From the bar chart in figure 4.30, it shows that both control method have a same effectiveness to compensate the harmonic current when the supply is a normal balanced and sinusoidal. However, when there is a distortion in the supply, either it is balanced and non-sinusoidal or unbalanced and sinusoidal voltage, the i_d-i_q control method gives a slightly better result as compared to the p-q control method. Nevertheless, the different in the performance of the two is not very significant. This slightly better performance of i_d-i_q method can be explained by looking at the different principle used in generating the harmonic current reference as described in the section followed.

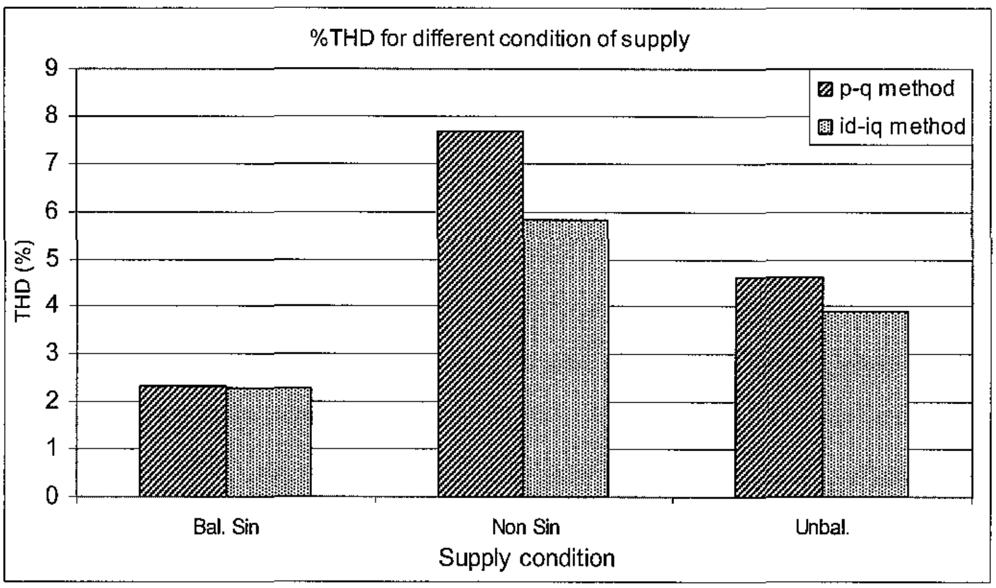


Figure 4.30: The comparison of the %THD of the input current for the combined system using i_d-i_q method and p-q method with different supply condition

i. Comparison between the p-q method and i_d-i_q method

The slightly better performance of i_d-i_q method in compensating the harmonic current from the p-q method for distorted supply condition but gives almost the same result for undistorted supply can be explained by the different principle used by both methods. Noted that the p-q control method is based on the stationary frame ($\alpha\beta$) and the i_d-i_q method is based on the synchronous frame (d-q). In order to assist the comparison, the i_d-i_q method will be derived in term of $\alpha\beta$ frame so that the different is clearly seen. The relationship of $\alpha\beta$ and d-q frame is shown in figure 4.31 where θ is the instantaneous voltage vector angle and voltage and current vectors are represented in of $\alpha\beta$ and d-q frame.

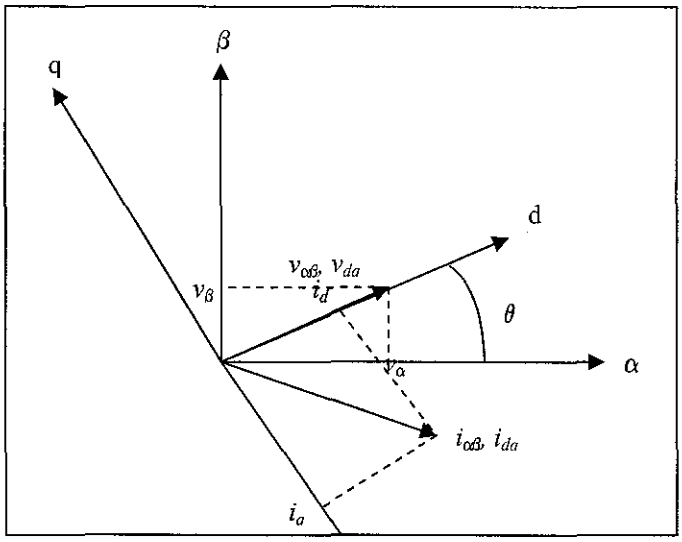


Figure 4.31: Voltage and current space vectors in stationary and rotating frames

In p-q control method, the voltage and current is transform into $\alpha\beta$ frame which is a stationary frame and the reference harmonic current is derived from instantaneous active and reactive power, p_S and q_S. p_S and q_S is the result from multiplication of voltage and current in $\alpha\beta$ coordinate and is given as:

$$\begin{bmatrix} p_S \\ q_S \end{bmatrix} = \begin{bmatrix} v_{L\alpha} & v_{L\beta} \\ v_{L\beta} & -v_{L\alpha} \end{bmatrix} \cdot \begin{bmatrix} i_{S\alpha} \\ i_{S\beta} \end{bmatrix} = \begin{bmatrix} P_S + \tilde{p}_s \\ Q_S + \tilde{q}_s \end{bmatrix}$$

Where p_S and q_S can be decomposed into oscillatory and average term, $P_S + \tilde{p}_s$ and $Q_S + \tilde{q}_s$.

In i_d-i_q control method, the harmonic reference current is obtained from the instantaneous active and reactive current component, i_d and i_q as shown in previous section. The d-q load current component is derived from a synchronous reference frame based on the Park's transformation and by referring to figure 4.31, the i_d and i_q is given as:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}, \ \theta = \tan^{-1}\frac{v_\beta}{v_\alpha}$$

Under balanced and sinusoidal mains voltage condition, angle θ is a uniformly increasing function but under distorted supply voltage due to voltage harmonics or unbalanced, the rate of $d\theta/dt$ may not be constant over a mains period. Substituting cosine and sine in term of voltage in $\alpha\beta$ coordinate, it become:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{1}{\sqrt{v_\alpha^2 + v_\beta^2}} \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

The transformation above is done where the direct voltage component, $v_d = |v_{dq}| = |v_{\alpha\beta}| = \sqrt{v_\alpha^2 + v_\beta^2}$ and the quadrature voltage component is always zero, $v_q = 0$.

The normal way of i_d-i_q control method is to decomposed the d-q current component into oscillatory or ac and fundamental or dc component by filtering it through low-pass filter. However, the derivation will be done in term of active and reactive power instead since the intention is to compare with the p-q control method. The Park's transformation applied in i_d-i_q method is a simple rotation of angle which applied to both voltage and current space vector. The active and reactive power are invariant under this transformation and thus it guarantees the power invariance when using the i_d-i_q control method. Therefore, as the reference frame is chosen in such a way that $v_q = 0$, the load powers can be written as:

$$\begin{bmatrix} p_S \\ q_S \end{bmatrix} = v_d \cdot \begin{bmatrix} i_d \\ -i_q \end{bmatrix}$$

which can be decomposed into fundamental and oscillatory component as:

$$\begin{bmatrix} P_S + \tilde{p}_s \\ Q_S + \tilde{q}_s \end{bmatrix} = V_d + \tilde{v}_d \cdot \left(\begin{bmatrix} I_d + \tilde{i}_d \\ -I_q - \tilde{i}_q \end{bmatrix} \right)$$

where P_s, Q_s, V_d and I_d represent the fundamental or dc component and $\tilde{p}_s, \tilde{q}_s, \tilde{v}_d, \tilde{i}_d$ and $\tilde{i}_q$ represent the oscillatory component. In p-q control method, the product of voltage and currents above will gives the power components which are then filtered out by using low-pass filter to get the harmonic power components. However, in i_d-i_q control method, the filtering action is performed over the load current components which give the harmonic current component. The difference of this operation results in different performance of both methods in different condition of supply voltage. Under balanced and sinusoidal supply voltage, the oscillatory voltage component $\tilde{v}_d$ is zero; thus the equivalent compensation powers for p-q control method, p_{c1} and q_{c1} are equal to the equivalent compensation powers for *id-iq* control method, p_{c2} and q_{c2}.

$$\begin{bmatrix} p_{c1} \\ q_{c2} \end{bmatrix} = \begin{bmatrix} p_{c2} \\ q_{c2} \end{bmatrix} = V_d \cdot \begin{bmatrix} \tilde{i}_d \\ -\tilde{i}_q \end{bmatrix}$$

Thus, this verify the result where both control methods gives almost similar performance in compensating harmonic current for undistorted supply condition. However, under unbalanced and non-sinusoidal supply voltage conditions, $\tilde{v}_d$ is no longer zero and need to be considered. For p-q control method, $\tilde{v}_d$ is amplified by the average and oscillatory current since the filtering operation is performed over the power components while the i_d-i_q method does not have this effect because the harmonic current is obtained by filtering out the load current component. The equivalent compensation power of p-q method and i_d-i_q method is given below respectively:

$$\begin{bmatrix} p_{c1} \\ q_{c2} \end{bmatrix} = -V_d \cdot \begin{bmatrix} \tilde{i}_d \\ -\tilde{i}_q \end{bmatrix} - \tilde{v}_d \cdot \left(\begin{bmatrix} I_d + \tilde{i}_d \\ -I_q - \tilde{i}_q \end{bmatrix} \right)$$

$$\begin{bmatrix} p_{c2} \\ q_{c2} \end{bmatrix} = V_d \cdot \begin{bmatrix} \tilde{i}_d \\ -\tilde{i}_q \end{bmatrix} - \tilde{v}_d \cdot \begin{bmatrix} \tilde{i}_d \\ -\tilde{i}_q \end{bmatrix}$$

Therefore, the different between these two methods under distorted supply condition can be expressed as:

$$\begin{bmatrix} p_{c1} \\ q_{c2} \end{bmatrix} - \begin{bmatrix} p_{c2} \\ q_{c2} \end{bmatrix} = -\tilde{v}_d \cdot \begin{bmatrix} I_d \\ -I_q \end{bmatrix}$$

From here, it is understood that the additional disturbance in the compensation power of p-q method makes the performance of id-iq method slightly better under the condition of unbalanced and non-sinusoidal supply. The contribution is significant due to the multiplication of the oscillatory voltage and fundamental current component.

Despite the better performance, it can be said that both method gives a satisfactory performance and does not show a significant different for this combination of filters as obtained when it applies to shunt active filter done by [19]. This can be understood since the harmonic current generated is only used to control the series active filter by imposing high impedance at harmonic frequencies. The series active filter basically performed as a harmonic isolator only and does not directly compensate the harmonic in the line. The compensation of harmonic is mainly done by the shunt passive filter that is designed to filter the fifth and seventh order of harmonic. Thus, the different method of control for active filter does not give a significant effect in the compensation performance of the combination filter. In conclusion, it can be stated that under balanced and sinusoidal supply, p-q method and i_d-i_q method have the same performance but the later method gives a better performance under unbalanced and non-sinusoidal supply. However, the effect of this slightly better performance of i_d-i_q method does not have a significant impact for the combination of series active filter and shunt passive filter.

4.2.4 Shunt Passive filter

As shown in previous discussion, the shunt passive filter played an important role in compensates harmonic in the network. The filter is tuned to the fifth and seventh harmonic only since that is the dominant harmonic in the load current. The combined filter system had improved the characteristic of the shunt passive filter and eliminates the series and parallel resonance. This is achieved since the series active filter had imposed high impedance across the network and allows the design of shunt passive filter to be insensitive to resonance. Thus, the selection of inductor and capacitor value become easier. However, a proper selection of these components is still need to be considered. Filter designed in the previous section require a lossless coils and capacitors to obtain the theoretical responses predicted. In practical world, capacitors are usually obtainable that have low losses, but inductors are generally lossy, especially at lower frequencies. Losses can be defined in terms of Q, quality factor of a reactive component If a lossy coil or capacitor is resonated in parallel with a lossless reactance, the ratio of resonant frequency to 3-dB bandwidth of the resonant circuit's impedance, i.e the band over which the magnitude of the impedance remains within 0.707 of the resonant value is given by:

$$Q = \frac{f_o}{BW_{3dB}}$$

The Qs of inductors and capacitors can be calculated by following equation respectively:

$$Q = \frac{\omega_n L}{R_L}$$

$$Q = \omega_n C R_c$$

Using elements having a finite Q in a design intended for lossless reactance has the following mostly undesirable effects:

1. At the passband edge, the response shape becomes more rounded. Within the passband, the ripples are diminished and may completely vanished.
2. The insertion loss of the filter is increased. The loss in the stopband is maintained so the relative attenuation between the passband and the stopband is reduced

Thus, the quality factor of the filter is also determine the characteristic of the filter. In choosing an optimum value of the filter, a smaller value of inductor possible is taken since the inductor is generally lossier than capacitor. From economical point of view, the inductor is also more costly as compared to the capacitor. Thus, the selection of the inductor and capacitor value is done in consideration of these factors. Since the filter is tuned to certain frequency, which is 250Hz and 350Hz, the inductor and capacitor value can only be chosen at proportional value to maintain the cut-off frequency. Impedance of an inductor is proportional to its inductance but the impedance of capacitor is inversely proportional to its capacitor. Thus, when the inductor value is decreased, the capacitor value must be increased to have the same cut-off frequency.

CHAPTER 5

CONCLUSION

A study on the performance of the combination of series active power filters and shunt passive filter based on two control methods are successfully done in this project. The model of the thyristor converter supplied by three phase voltage was developed using MATLAB-Simulink. The performance of each filter acting alone and their combination had been carried out at the first phase. The constructed model was first tested for without any filter operating on it, then with only shunt passive filter operating, followed by with only series active filter operating and then with both filters operating on it. For each case, the input and output current waveform is monitored and the THD value of input current is presented. The result shows that the compensation of the harmonic current by series active filter is lower than the compensation by shunt passive filter acting alone. However, the harmonic compensation is enhanced tremendously for the combined filter. The extended study on the combined filter using two different control methods which are the instantaneous active and reactive power theory (p-q method) and the instantaneous active an reactive current component (i_d-i_q method) is done over three different supply conditions. From the analysis of the harmonic content in the input line current (THD), it can be stated that under balanced and sinusoidal supply, p-q method and i_d-i_q method have the same performance in compensating the harmonic. Nevertheless, under unbalanced and non-sinusoidal supply, the i_d-i_q method had given a better performance for harmonic compensation. Despite this slightly better performance of i_d-i_q method, it can be concluded that it does not have much significant impact for the combination of series active filter and shunt passive filter in compensating the harmonic.

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